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A MESO-SYNOPTIC ANALYSIS OF THE THUNDERSTORMS ON 28 AUGUST 1958

BY

D. E. PEDGLEY, B.Sc.

LONDON : HER MAJESTY'S STATIONERY OFFICE

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A MESO-SYNOPTIC ANALYSIS OF THE THUNDERSTORMS ON 28 AUGUST 1958

SUMMARY

The thunderstorms of 28 August 1958 over the south-eastern half of England were remarkable for the rapid changes of atmospheric pressure which accompanied them. A maximum rise of about five millibars and a maximum fall of about five millibars were observed. By using methods of meso-synoptic analysis, pressure, winds, rainfall, thunder and clouds were analysed separately. Data were all available routinely, and were mostly from synoptic stations and autographic records.

Meso-scale charts are presented at hourly intervals for the period 0600–1800 GMT, and from them detailed descriptions of the structure and evolution of six meso-systems—containing both highs and lows—were obtained. Using these, a model meso-system was built up which was found to pass through three stages having the following main properties:

(i) Growth stage. Storms are isolated or in small groups. Local pressure rises develop, eventually merging into a " thunderstorm high ", which then grows in areal extent and in amplitude along with a growing rain area.

(ii) Mature stage. The rainfall pattern becomes more organized, with the separate storms being replaced progressively by a row of intense cells along the leading edge of the high together with a broad area of continuous rain behind it. This high is more intense and continues to grow in extent. Its leading edge is marked by a very large pressure gradient, and its centre corresponds to the position of the most violent storms which seem to be self-propagating and able to move in a direction across that of the winds at low levels. After some hours at this stage a " wake low " appears behind the high, with pressure falling well below undisturbed values. The rear edge of the rain and thunder corresponds very well to the axis of this low.

(iii) Decay stage. The line of storms disappears, leaving a broad area of uniform rain which itself slowly disperses over a period of many hours. Although the areal extent of the system continues to increase, the magnitudes of the pressure fluctuations decrease until they become too small to be measured.

The origin of pressure changes in thunderstorms is reviewed; they are found to be caused by the storms, not vice versa. The pressure rises are largely caused by evaporational cooling of air below cloud base when rain falls through it. With some reasonable assumptions, the maximum rise, ΔP millibars, is found to depend on the cloud base height, h kilometres, in the following way:

$$\Delta P = 0{\cdot}8h^2.$$

Possible causes of departure from this maximum are indicated.

The storms were of a type caused by the release of potential instability in an air mass, brought about by divergence aloft. Development of the instability by differential advection is discussed and compared with results from other studies of severe storms.

The self-propagating nature of the storms in the mature stage is investigated, and also the significance of vertical wind shear to their structure and development. One storm mass was found to move across the motion of individual cells at an angle about 9° to the right.

§ 1—INTRODUCTION

1.1 *The storms*

On Thursday 28 August 1958, thunderstorms were reported from a wide area of England south-east of a line lying roughly from mid-Lincolnshire to east Dorset. Some of these storms were severe and were accompanied by torrential rain, much thunder and lightning and, in parts of East Anglia and south-east England, skies so dark that artificial lighting was needed even at midday. Such violence alone is sufficient to attract the attention of the public, so that it is not surprising that the storms made headline news in the Press.

However, these storms had other characteristics which made them of special meteorological interest. Firstly, they were accompanied by large fluctuations in atmospheric pressure. Pressure changes of one or two millibars are commonly found with thunderstorms, but with these storms the largest ranges through which pressure changed were five to eight millibars, quite exceptional for Britain. Figures 2(*a*)–(*q*) show some typical barograms with the pressure fluctuations very well marked. Secondly, the storms moved so quickly that the effects of their passing were felt over a wide area. Because of this, something of their life-histories could be found by studying the records from successive places over which the storms moved. Lastly, the storms were of a type which develop at medium levels as a result of convergence in a potentially unstable atmosphere, and they were therefore of a type which can occur at any time of the day or night, since they do not need the " trigger action " of day-time surface heating to start them.

These storms were eminently suitable as the subject of a case-study to discover some of the properties of the weather systems which accompany widespread thunderstorms. To do this, detailed large-scale synoptic charts were prepared, with short time intervals between them. The need for detail in space and time—much more detail than is required for everyday synoptic analysis—arises from the smaller size and shorter life of a typical weather system found under these conditions. It may be 50 to 100 miles in diameter and last for 5 to 10 hours. A weather system of this type is known as a meso-system, and the scale of synoptic analysis used in its study is meso-synoptic analysis.

Many case-studies have already been made using meso-synoptic analysis, mostly in the United States of America and Japan, and these will be referred to in Section 3. This study has been undertaken with three aims in mind:

(i) to show that meso-synoptic analysis is possible with routinely available data,

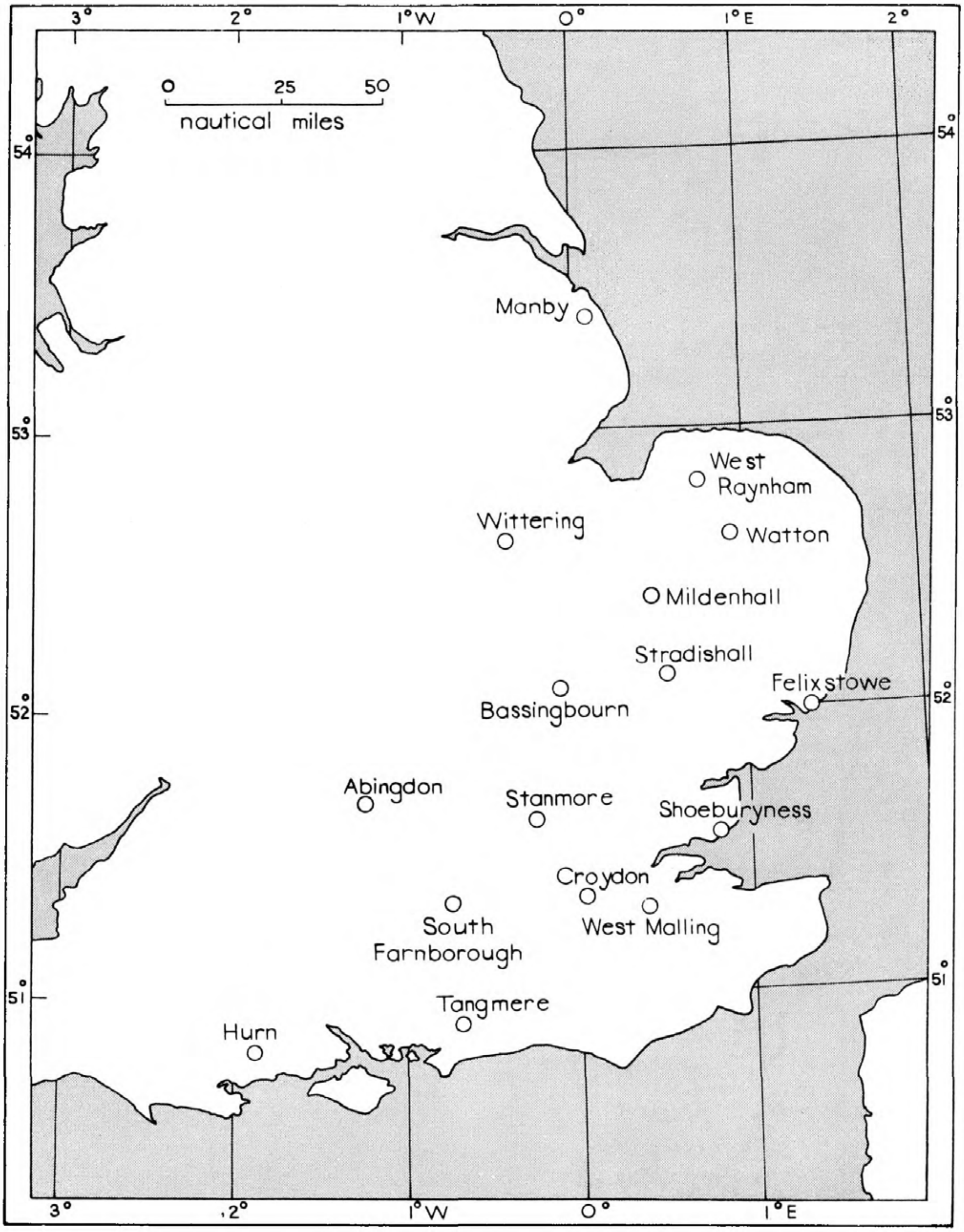
(ii) to investigate some of the properties of meso-systems associated with widespread thunderstorms,

(iii) to determine whether at least some of the techniques of meso-synoptic analysis can be used in day-to-day weather forecasting.

By means of the results given in Sections 2 and 3 it will be shown that the first aim has been realized. It will also be found that the meso-systems which crossed England on 28 August 1958 had many features in common with meso-systems found in other parts of the world. The last aim has been realized, at least in part, by an increase in knowledge of typical meso-systems sufficient to produce a " model ".

1.2 *Meso-synoptic analysis*

The detail required for meso-synoptic analysis means that the observing stations must form a network denser than that used for ordinary analysis. A spacing of 10 to 20 miles is about ideal. Fortunately, the storms studied here passed over a part of England where the regularly reporting synoptic stations are relatively closely spaced, but even so, many more data were used to help fill the gaps in the network—data from sources to be described in the next section.


3°
2°
1°W
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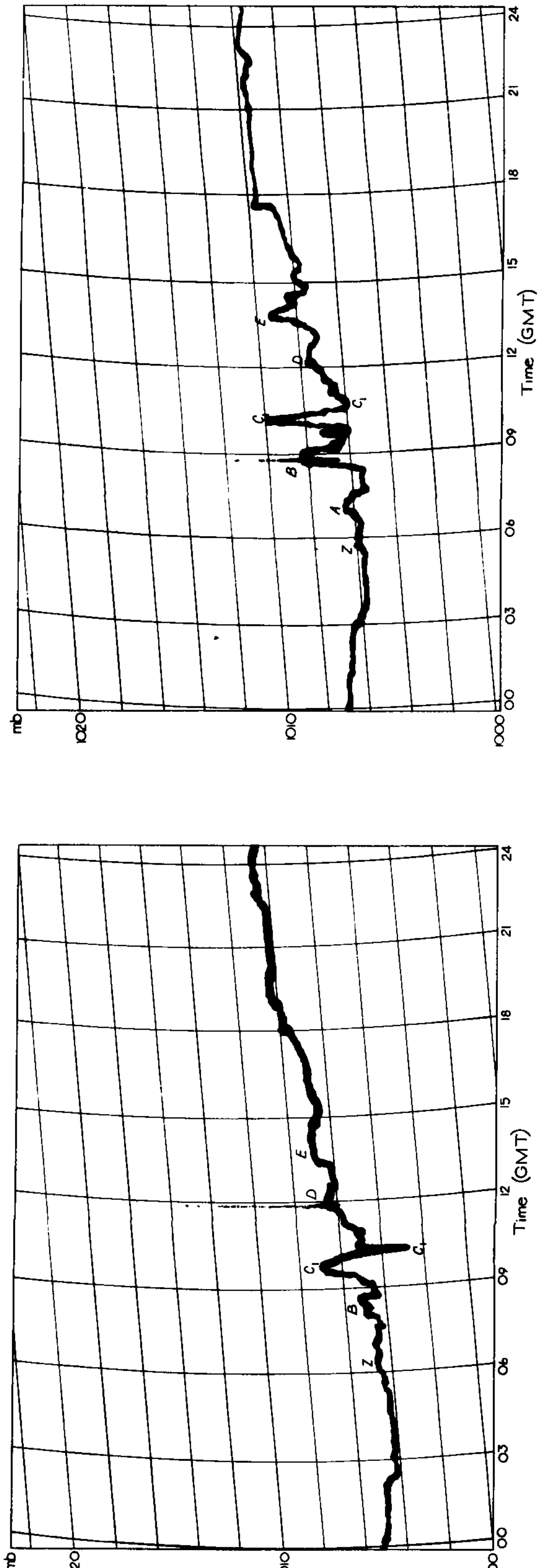
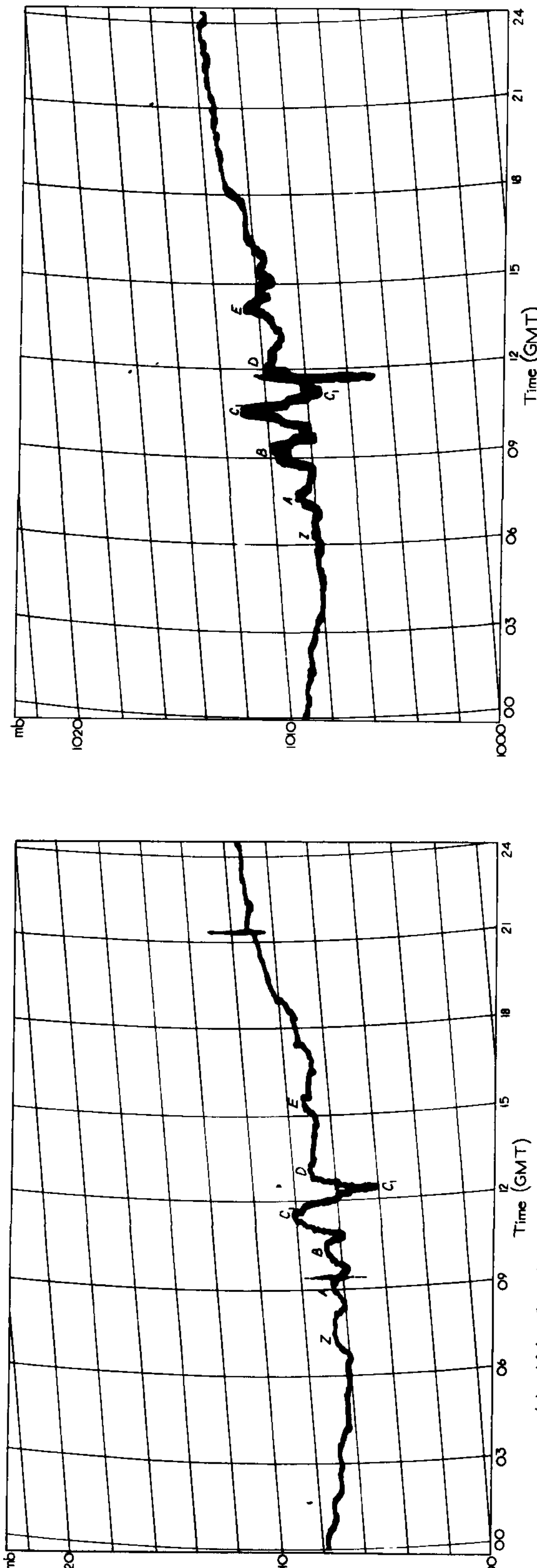
0 25 50
nautical miles
54°
53°
52°
51°
Manby
West Raynham
Wittering
Watton
Mildenhall
Stradishall
Felixstowe
Bassingbourn
Abingdon
Stanmore
Shoeburyness
Croydon
South Farnborough
West Malling
Tangmere
Hurn

FIGURE 1—POSITIONS OF STATIONS WHOSE BAROGRAMS ARE ILLUSTRATED IN FIGURE 2



(*a*) Hurn (30 min slow, 1·0 mb low)

(*b*) Tangmere (10 min slow, 0·2 mb high)

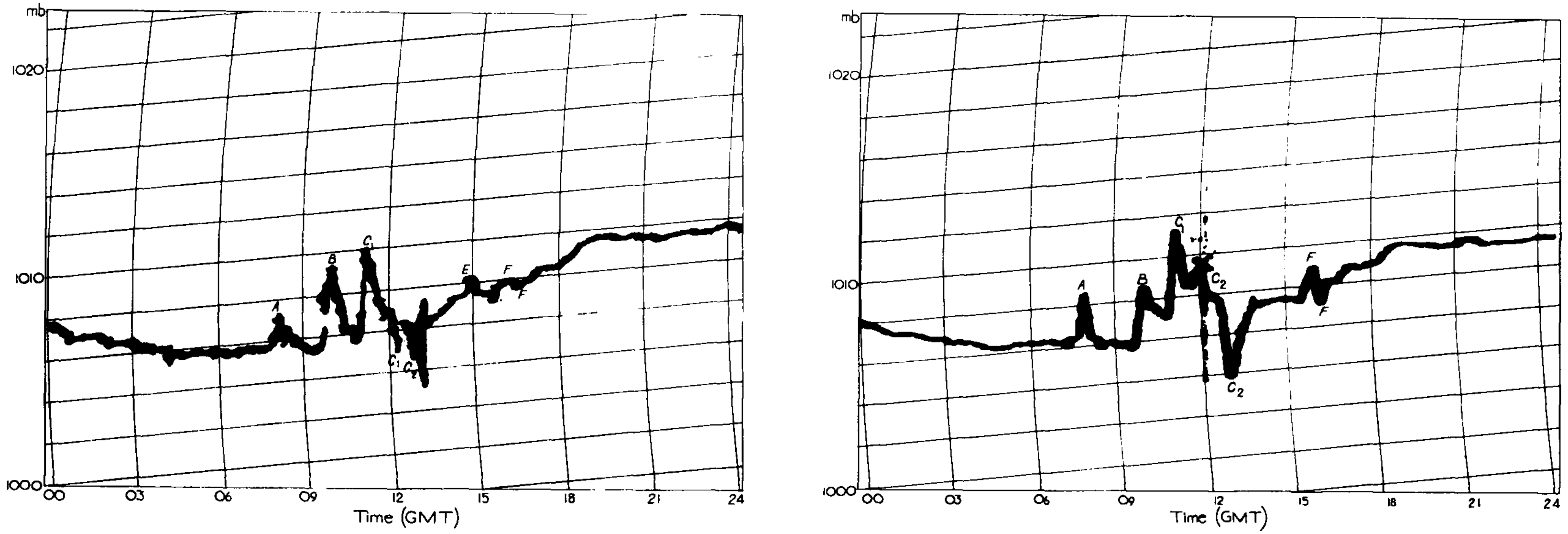


(*c*) Abingdon (30 min fast, pressure correct)

(*d*) South Farnborough (20 min slow, 1·5 mb high)

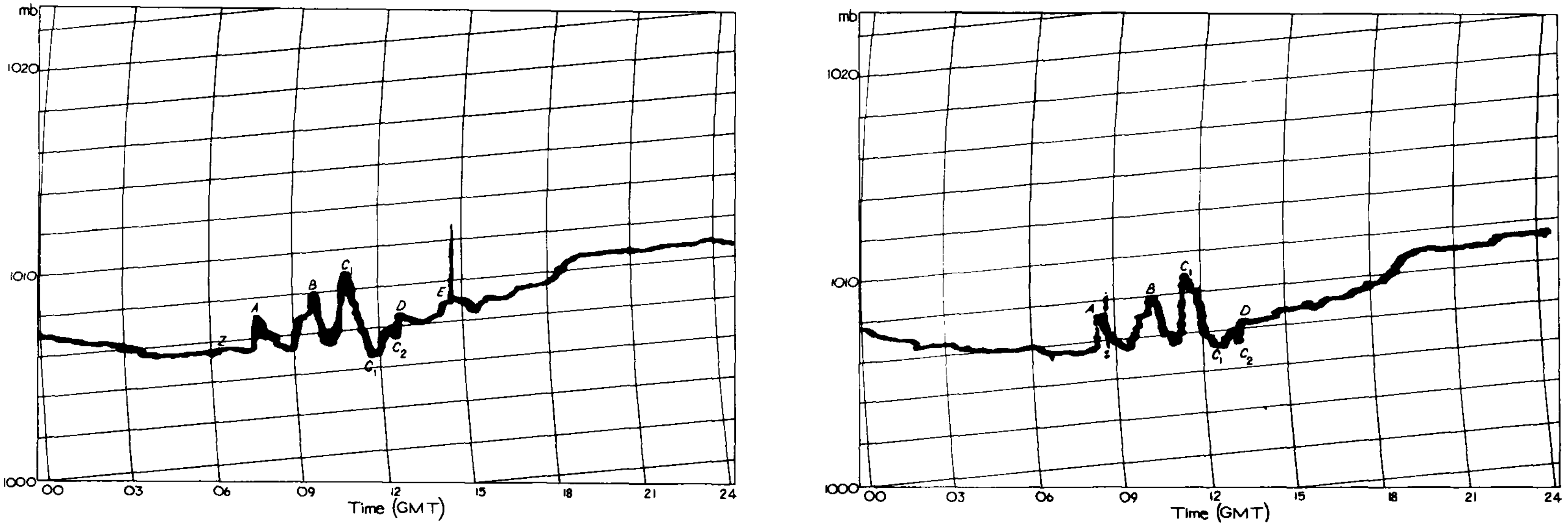
FIGURE 2—SOME EXAMPLES OF BAROGRAMS FOR THE PERIOD 0600 TO 1800 GMT, 28 AUGUST 1958, ILLUSTRATING DETAILS OF PRESSURE FLUCTUATIONS

The lettering identifies the meso-systems described in Section 3.2.



(*e*) Croydon (time correct, 0·3 mb low)

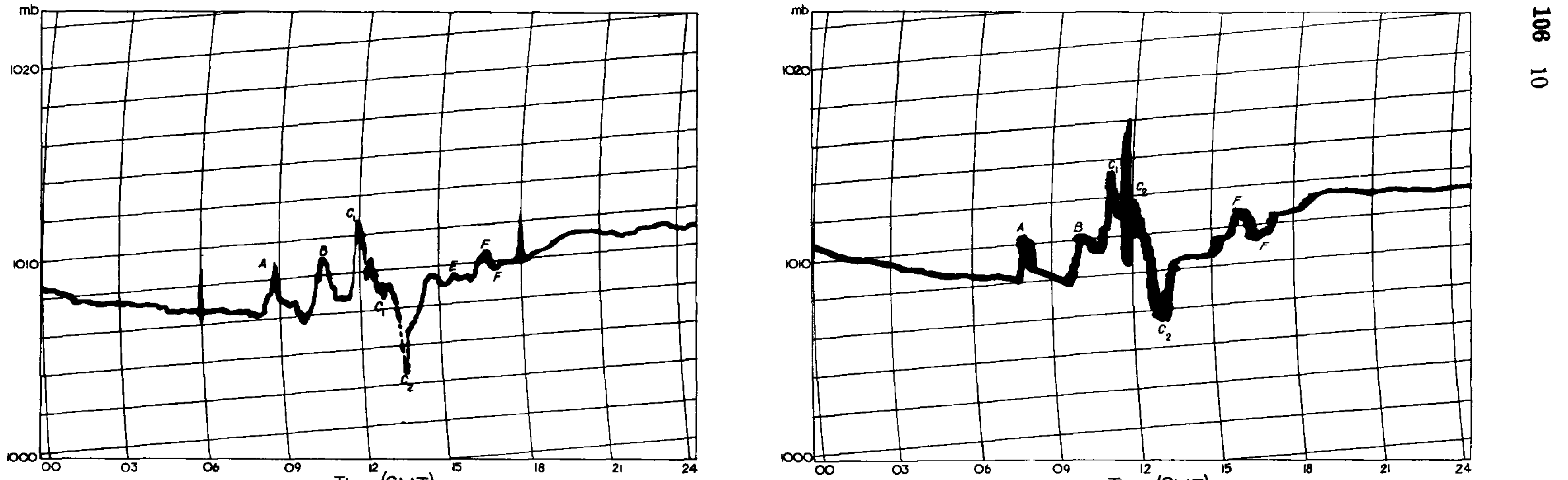
(*f*) West Malling (5 min fast, pressure correct)



(*g*) Stanmore (25 min slow, 0·5 mb low)

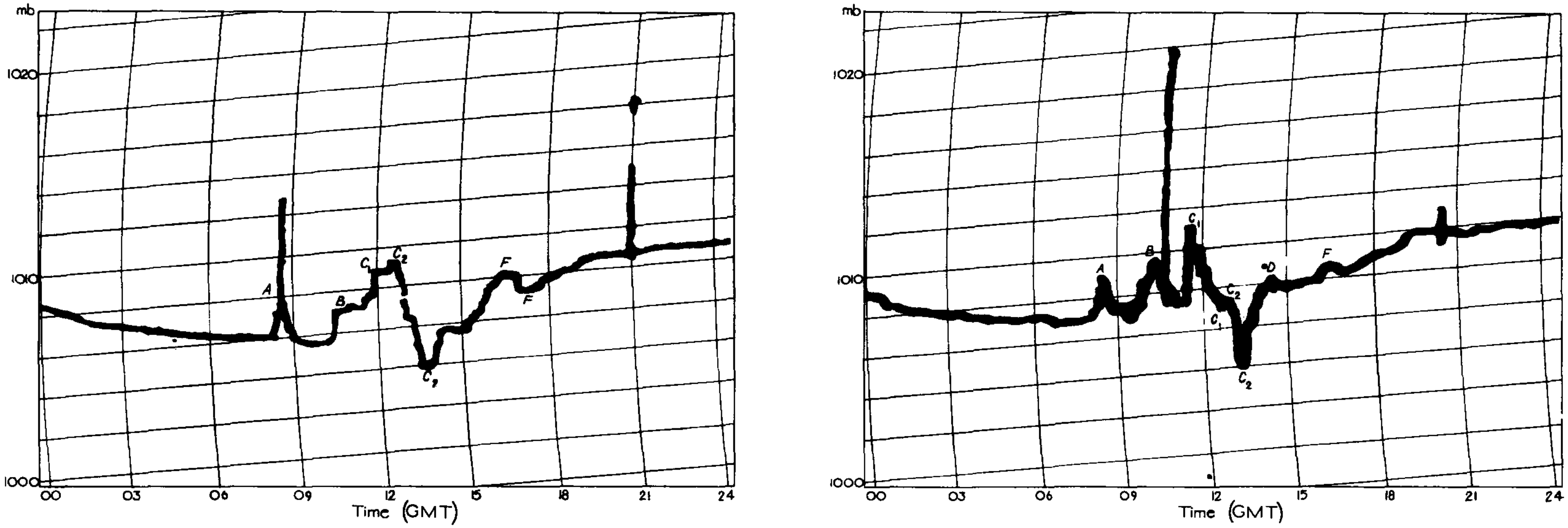
(*h*) Bassingbourn (5 min slow, pressure correct)

FIGURE 2—SOME EXAMPLES OF BAROGRAMS FOR THE PERIOD 0600 TO 1800 GMT, 28 AUGUST 1958 (continued)
The lettering identifies the meso-systems described in Section 3.2.



(*i*) Stradishall (time correct, pressure correct)

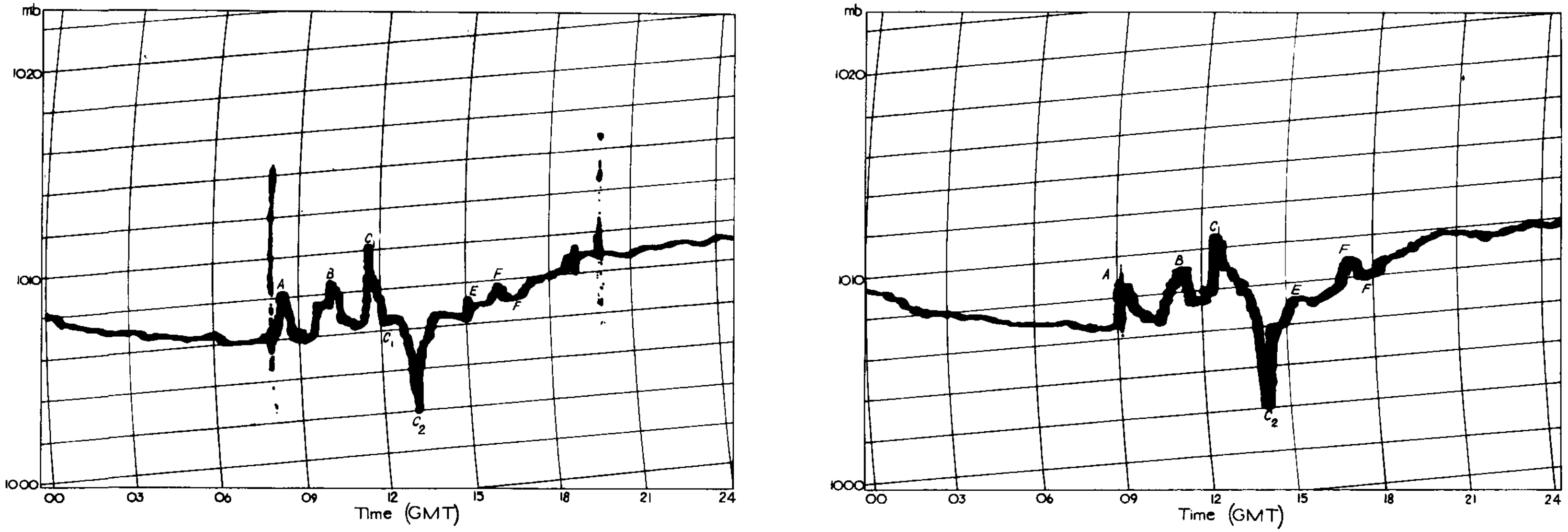
(*j*) Shoeburyness (15 min slow, 1·6 mb high)



(*k*) Felixstowe (15 min slow, 0·8 mb low)

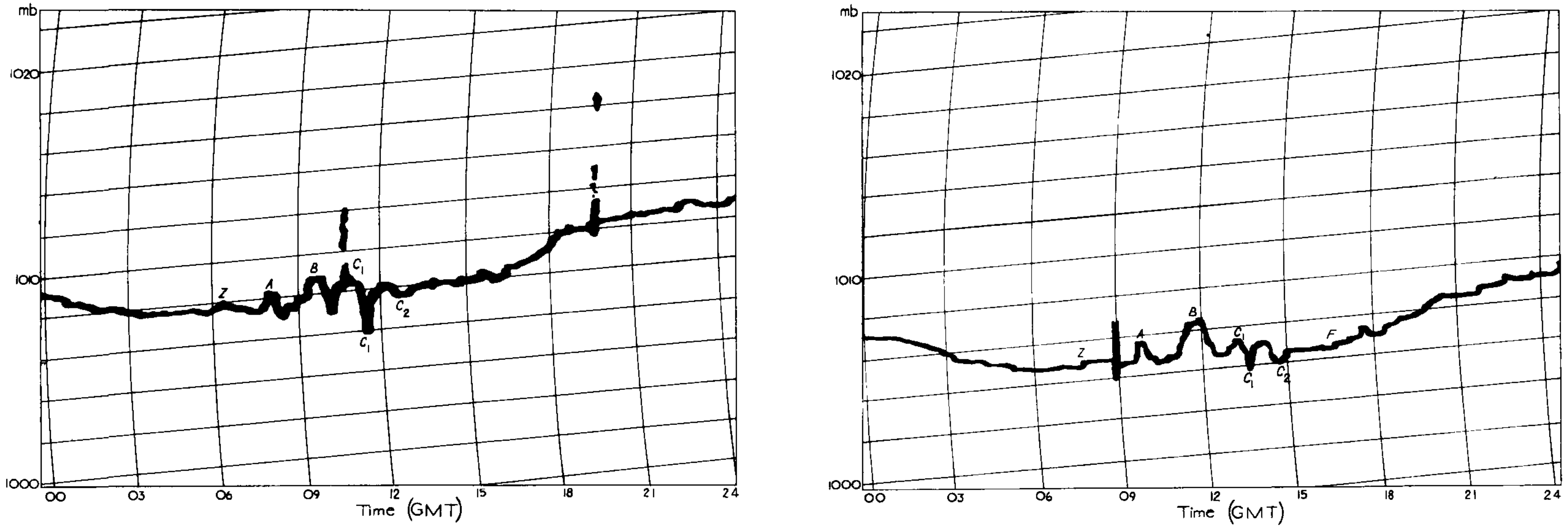
(*l*) Mildenhall (30 min slow, 0·5 mb high)

FIGURE 2—SOME EXAMPLES OF BAROGRAMS FOR THE PERIOD 0600 TO 1800 GMT, 28 AUGUST 1958 (continued)
The lettering identifies the meso-systems described in Section 3.2.



(*m*) West Raynham (10 min fast, pressure correct)

(*n*) Watton (time correct, 0·4 mb high)



(*p*) Wittering (75 min slow, 1·2 mb high)

(*q*) Manby (5 min slow, 1·0 mb low)

FIGURE 2—SOME EXAMPLES OF BAROGRAMS FOR THE PERIOD 0600 TO 1800 GMT, 28 AUGUST 1958 (continued)
The lettering identifies the meso-systems described in Section 3.2.

Such supplementary data, forming the larger part of those used in the analysis, whilst readily available after the event, are not normally available *synoptically*. Consequently, the details discovered by this study would not be apparent from the use of routine synoptic data alone. Not only must the observing stations be closely spaced but also the timing of weather changes must be as precise as possible. Next to the notes made by a vigilant observer the best timing is probably attained by autographic instruments. In most instances, the charts from such instruments used in this study did not have time scales sufficiently open for them to be read to an accuracy greater than about five minutes.

A special technique has been developed in meso-synoptic analysis whereby the amount of data available for places between the regularly reporting stations can be increased without increasing the number of stations. The technique consists of converting the time-sequence of events at a given station into a space-sequence along a line passing through that station and lying parallel to the direction of motion of the particular phenomenon which has passed over the station. For example, if a shower of rain falls at the station between 0850 and 0855 GMT and the shower is moving towards the north-east at 60 miles per hour, then this information could be plotted on the 0900 GMT chart as a shower lying between five and ten miles to the north-east of the station. The success of this method clearly depends upon the length of time one can expect the shower to retain its characteristics without significant change as it crosses the country. This time period varies with the weather element under consideration, pressure, rainfall, thunder, etc., and will be examined again in the next section. As a result of this technique, the amount of data available at the time of a meso-synoptic chart is greatly increased by the contribution of data for non-chart times which would otherwise be wasted. In this way, every significant event, whether observed by eye or recorded by autographic instruments, can be used in the analysis.

Although this Memoir is concerned with synoptic systems on a *meso*-scale, it must be emphasized that these systems possess detailed structures on a still smaller scale—one which is perhaps an order of magnitude less and which is commensurate with the size of individual storms. Meso-synoptic analysis is not designed to study such small-scale features but their existence and importance will be mentioned in passing.

§ 2—METHODS OF MESO-SYNOPTIC ANALYSIS

2.1 *Data used in the analysis*

A wide range of sources was used to obtain as large a supply of data as possible for the analysis. The following is a list of these sources:

(i) Copies of entries in the Daily Register of observations at each of the synoptic stations in the area concerned, controlled both by the Meteorological Office and by the United States Air Force. These entries included not only routine hourly (or half-hourly, or three-hourly) synoptic observations but also special reports and notes which were not broadcast by teleprinter.

(ii) Autographic records of pressure, wind and rainfall. (Temperature and humidity were not analysed because changes in these elements were mostly quite small.) These records were obtained from Meteorological Office stations, both synoptic and climatological, and from public bodies and private persons after advertising in the magazines *Weather* and *The Optician*.

(iii) Visual observations made by private persons, particularly by the network of volunteer thunderstorm observers organized by the Electrical Research Association Laboratory at Leatherhead, Surrey.

(iv) Photographs of the radar display obtained at the Meteorological Office, East Hill, Dunstable, Bedfordshire, and tracings of the radar display from the London Forecast Office, Kingsway, London, W.C.2.

(v) Newspaper reports of damage by lightning, of flooding, and of miscellaneous events associated with the storms, some of them amusing.

The different sources gave data of variable quality and reliability, but almost all of the vast amount which was finally collected was usable, either directly or after correction by methods to be described subsequently in this section. Every half-hour each of the weather elements, pressure, wind, rain (and hail), thunder and lightning, and cloud (only every hour) was analysed, independently as far as possible. However, only hourly charts are reproduced in Section 3.

2.2 *Analysis of pressure*

At first sight the fluctuations in pressure, such as those shown in Figures 2(*a*)–(*q*), seem bewilderingly complicated. But comparison of the changes observed at neighbouring stations shows that they are far from random. In fact each rise and fall shown on a barogram indicates the passing of a meso-anticyclone or a meso-depression respectively. The aim of the meso-analysis of pressure is to determine the sizes and movement of these meso-systems.

A typical barogram, recording the passing of meso-systems, usually resembles Figure 3. This shows several salient features, not all of which may be present on a given occasion:

(i) Micro-low. A sudden, small down-surge of short duration. Studies in the United States of America have shown that this is the result of a small-scale depression some five to ten miles in diameter, commonly accompanied by tornadoes. In this study no definite indications of the micro-low were observed.

(ii) Pressure surge. An abrupt change in the slope of the barogram trace, which sometimes becomes almost vertical.

(iii) Thunderstorm high. A roughly dome-shaped region (the pressure dome) where pressure is above the undisturbed value. The first part, or pressure rise, is sometimes very sudden with a jump of several millibars in five minutes or less. The highest pressure sometimes occurs as a sharply pointed pressure nose, in which case the rise from surge to nose usually takes 10 to 15 minutes. When there is no nose the rise may take 15 to 30 minutes, sometimes more.

(iv) Pressure drop. A rapid fall, either back to near undisturbed pressure or to below it. The rate of fall is seldom as large as the rate of rise after the pressure surge.

(v) Wake low. A V-shaped trough, larger than the micro-low, but not always present. After the wake low, pressure returns to near its undisturbed value.

Two sources of pressure data were available: synoptic reports (from about 80 stations) and barograms (about 110). Figure 4 shows the positions of stations reporting pressure. The synoptic reports were almost entirely of pressure corrected to mean sea level made hourly, on or near the hour. Twelve stations reported half-hourly and some stations only every three hours; a few reports were not of mean-sea-level pressure but of ICAO* altimeter pressure settings (QNH), the difference on this day seldom being more than 0·2 millibar. All measurements were made with Kew-pattern mercury barometers. The barograms were taken from aneroid barographs and, with the exception of the chart from Kew Observatory, were weekly charts. Almost all the barograms were of two types: those from Meteorological Office open-scale microbarographs, whose traces could be read to within 0·1 millibar and 5 minutes, and those from smaller barographs, where the traces could be read to within 0·5 millibar and 10 minutes. Although the barograms were read to these limits, the accuracy of the microbarographs was probably within about ±0·2 millibar and ±10 minutes, and the accuracy of the small barographs was only to within about ±0·5 millibar and ±10 minutes.

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* International Civil Aviation Organization.

Plotting the synoptic pressure reports on the meso-scale charts was simple. Readings were transferred directly from the copies of Daily Register entries on to the charts, the position of the reading being placed either upwind or downwind from the observing station according to whether the reading was made after or before the chart time respectively. It was assumed that the time of observation was that given in the Daily Register to the nearest minute. This is unlikely to be exactly true, but an error in time of five minutes would cause an error in placing the reading on the chart of only about five miles (taking the approximate speed of the meso-systems as 60 miles per hour) which is within the limits of accuracy of the meso-analysis.

Plotting the barogram data was more complex, and depended upon whether the barogram being used had time-marks and check readings or not. For each time-marked barogram (there were about 70 of them) the following data were extracted and placed on a card, the pressure card:

(i) Times and pressures at the extremes of the fluctuations, and of the pressure surges.

(ii) Notes on the general shape of each fluctuation—whether sharp or flat—and on those parts of the trace which were steady or had numerous small-scale changes.

(iii) Half-hourly values of pressure reduced to mean sea level.

All the times and pressures were corrected by using the time-marks and check readings. With each barogram that had neither time-marks nor check readings (about 40) corrections were made indirectly before the above data could be tabulated on pressure cards. These corrections were found in the following ways:

(i) Correction for timing. A salient feature of the trace was selected as a " natural time-mark ". By comparing the indicated time of this feature (in most instances the surge preceding the third thunderstorm high, since this was the most clear-cut and it occurred over the widest area) with the true time, a correction could be found which would apply to any position along the trace. The true time was found by first constructing a chart showing the times of occurrence of the given feature based upon those barograms which possessed time-marks, then drawing isochrones at half-hour intervals, and finally interpolating the true time of the particular feature at the place where the barogram without time-marks was obtained. Such an isochronic chart was constructed for each of the salient features of the barograms—for maxima and minima of pressure and for surges. Figure 5 shows an isochronic chart for the surge preceding the third thunderstorm high. An isochrone on this chart is also coincident with a line drawn on the meso-synoptic chart (for the time of the isochrone) joining places where the particular surge is occurring at the time of the chart. Such a line is called a surge line and it represents the leading edge of the thunderstorm high. Similarly, isochrones of maximum pressure are coincident with axes of thunderstorm highs, and isochrones of minimum pressure with axes of wake lows. Isobars were also drawn on the isochronic charts showing the pressure occurring at the passing of each of the barogram features.

(ii) Correction for pressure setting. The mean indicated pressure over the time interval used in the meso-analysis was estimated by eye from the barogram, and then compared with the true mean pressure. The true mean pressure was found by first calculating the mean pressures (corrected to mean sea level) for the period 0600 to 1800 GMT at each of the synoptic stations reporting pressure and then plotting the values on a chart. Isobars were next drawn so that the true mean pressure could be easily interpolated for the position of the barogram without check readings. Figure 6 shows the isobars of mean pressure for the period 0600 to 1800 GMT used for this correction.

Having tabulated the barogram features, the following data were plotted for the meso-synoptic analysis of pressure:

(i) Values of pressure corrected to mean sea level, obtained either from copies of the Daily Registers (for meso-synoptic charts on the hour) or from the pressure cards (for charts on the half-hour).

(ii) Positions of surge lines, and of axes of thunderstorm highs and wake lows, obtained from the isochronic charts.

(iii) Positions of intersections of isobars and isochrones on the isochronic charts since these are coincident with the intersections of surge lines (or axes) and isobars on the meso-synoptic charts.

The analysis of pressure was completed by drawing isobars at one-millibar intervals based on the plotted data and considering the positions of surge lines, axes, notes from the pressure cards and, above all, continuity from one chart to the next. In Section 3, meso-synoptic analyses of pressure are shown at hourly intervals from 0600 to 1800 GMT.

2.3 *Analysis of winds*

The rapid changes in wind velocity at a station as the meso-systems pass over seem almost as random as the fluctuations in pressure. Some examples of anemograms are shown in Figures 7(*a*)–(*d*). But again the randomness is an illusion. The apparently rather light and variable winds really conform to definite patterns—it would be quite wrong to dismiss their vagaries as being " just thunderstorm winds " lacking any order. However, the wind patterns are often quite different from those produced by flow under balanced forces. In Section 4.2 the relation between wind and pressure patterns will be discussed in detail.

Two sources of wind data were available: synoptic reports (from about 100 stations) and anemograms (28). Figure 8 shows the positions of stations reporting winds. The synoptic reports were mostly made hourly, on or near the hour. Twelve stations reported half-hourly and some stations only every three hours. The anemograms were taken from either pressure-tube or electrical anemographs, and had scales sufficiently open that they could be read to within one knot, ten degrees, and about one minute. However, times were noted to the nearest five minutes, but speeds to ± 1 knot and directions to the nearest ten degrees. With a few anemograms the speed was suspected to be too small. Small corrections were estimated in these instances.

Plotting the synoptic wind reports on the meso-scale charts was as simple as plotting the synoptic pressure reports. Readings were transferred directly from the copies of the Daily Register on to the charts, taking into account the differences between observation time and chart time as described above. All the anemograms had sufficient time-marks and from them the following data were extracted and placed on cards, the wind cards, one for each anemogram:

(i) Times and velocities of sudden changes, both speed and direction, veering and backing, and of steady winds or calms.

(ii) Times and velocities of maximum gusts.

(iii) Half-hourly values of wind velocity.

Having tabulated the anemogram features, the following data were plotted (superimposed upon the meso-synoptic charts of pressure):

(i) Values of wind velocity, using conventional symbols with a full barb representing ten knots and a half barb five knots. They were obtained either from copies of the Daily Register (for meso-synoptic charts on the hour) or from the wind cards (for charts on the half-hour).

(ii) Values of wind velocity at times of sudden change, obtained from the wind cards and from notes in the Daily Register copies. These were plotted upwind or downwind from the station according to whether the change occurred after or before the chart time, respectively. If the change took place more than 15 minutes from chart time it was not used on that chart but was transferred to the chart whose time was within 15 minutes of the change.

In Section 3, meso-synoptic charts of winds are shown at hourly intervals from 0600 to 1800 GMT.

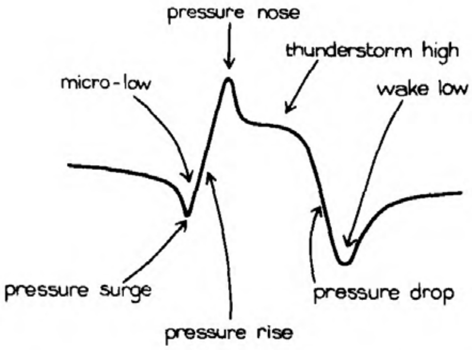

pressure nose
thunderstorm high
micro-low
wake low
pressure surge
pressure rise
pressure drop

FIGURE 3—TYPICAL FEATURES OF A BAROGRAM SHOWING THE PASSING OF MESO-SYSTEMS

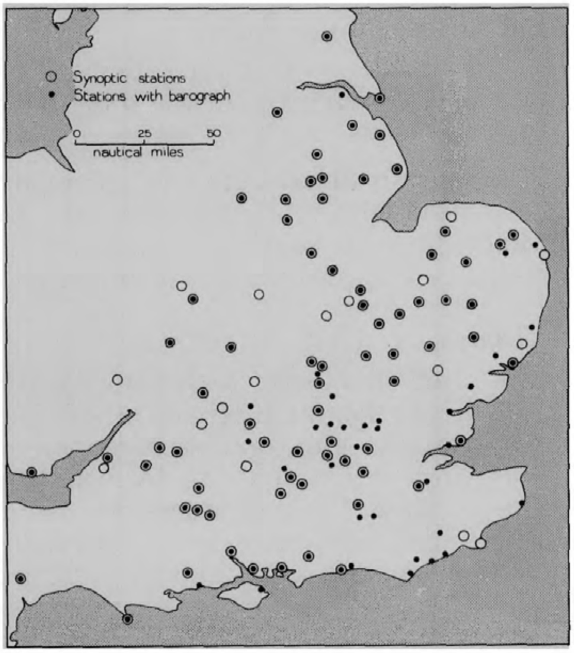

○ Synoptic stations
• Stations with barograph
0 25 50
nautical miles

FIGURE 4—POSITIONS OF STATIONS RECORDING PRESSURE

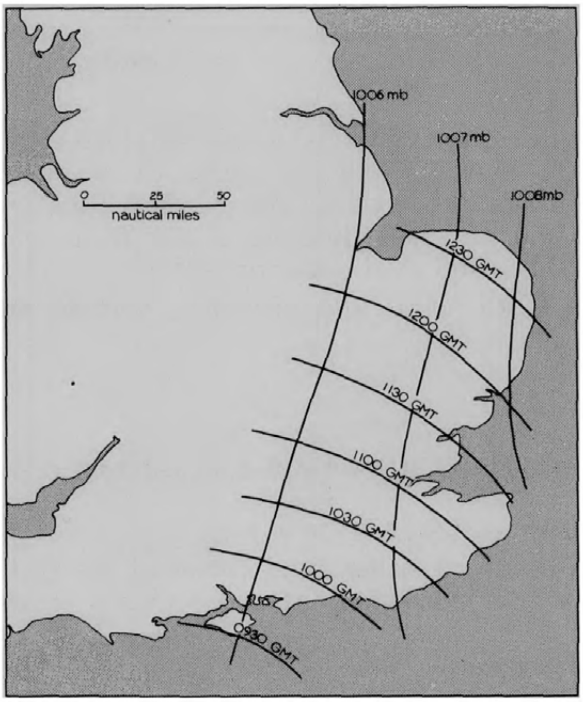

1006 mb
1007mb
1008mb
0 25 50
nautical miles
1230 GMT
1200 GMT
1130 GMT
1100 GMT
1030 GMT
1000 GMT
0930 GMT

FIGURE 5—ISOCHRONIC CHART FOR SURGE LINE PRECEDING HIGH *C*, AND ISOBARS SHOWING PRESSURE AT TIME OF COMMENCEMENT OF RISE

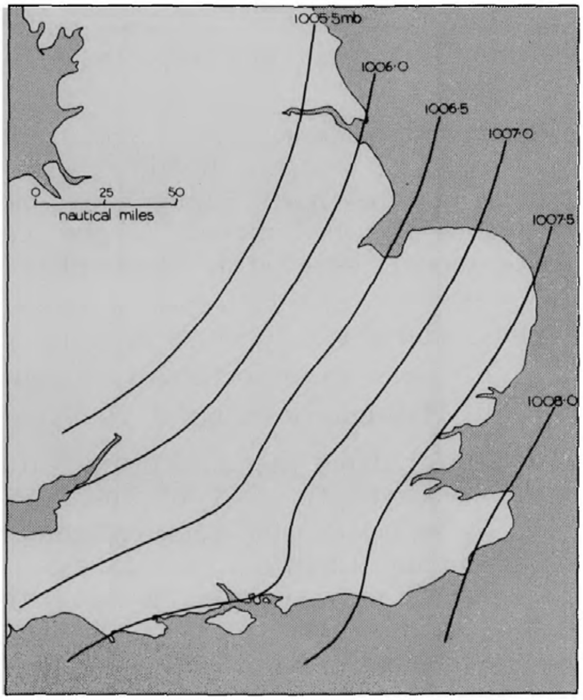
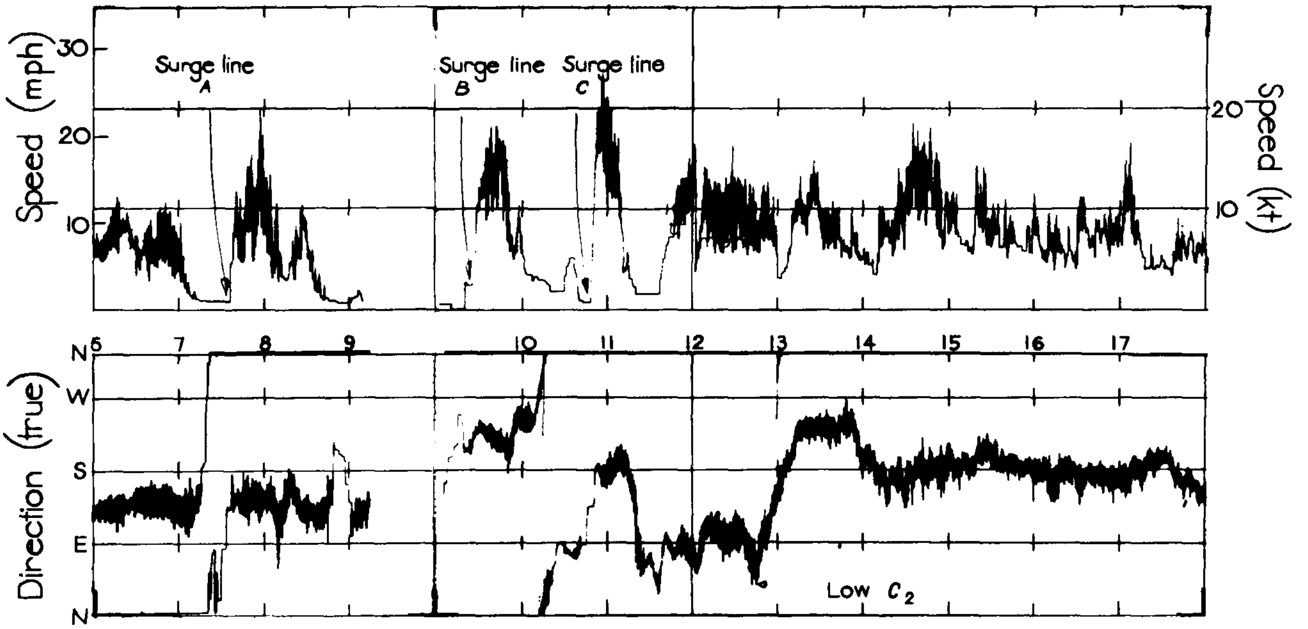
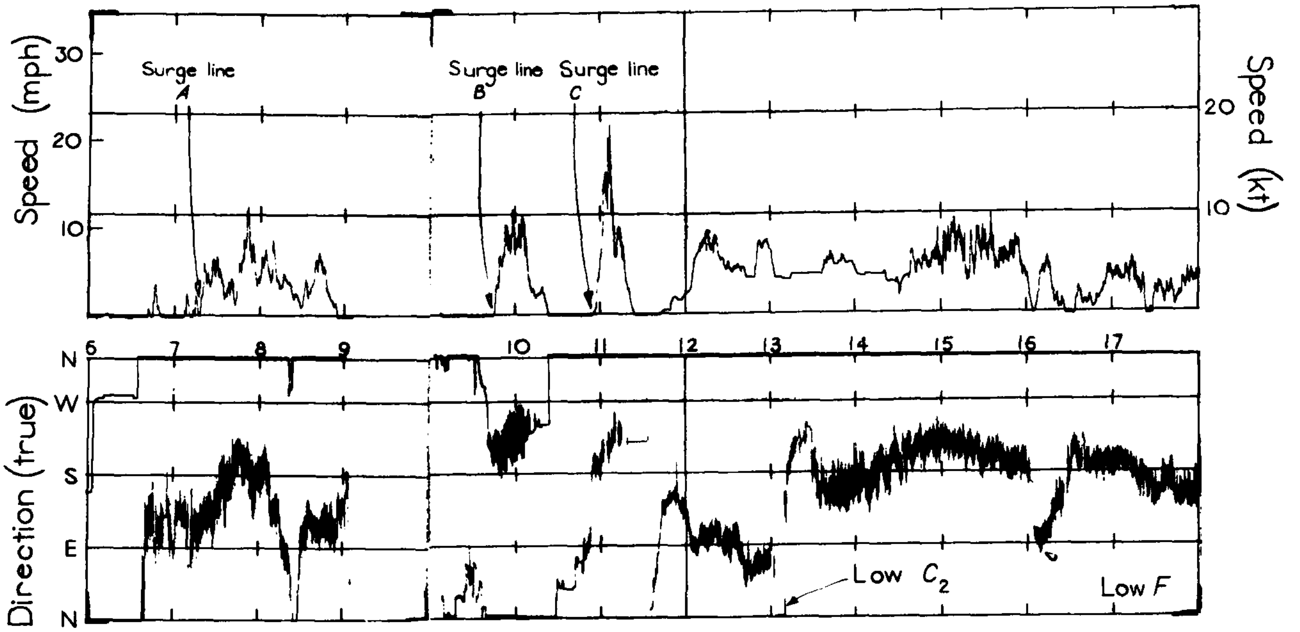

1005·5mb
1006·0
1006·5
1007·0
1007·5
1008·0
0 25 50
nautical miles

FIGURE 6—ISOBARS OF MEAN PRESSURE, 0600 TO 1800 GMT, 28 AUGUST 1958, BASED MAINLY ON 13 HOURLY READINGS AT SYNOPTIC STATIONS

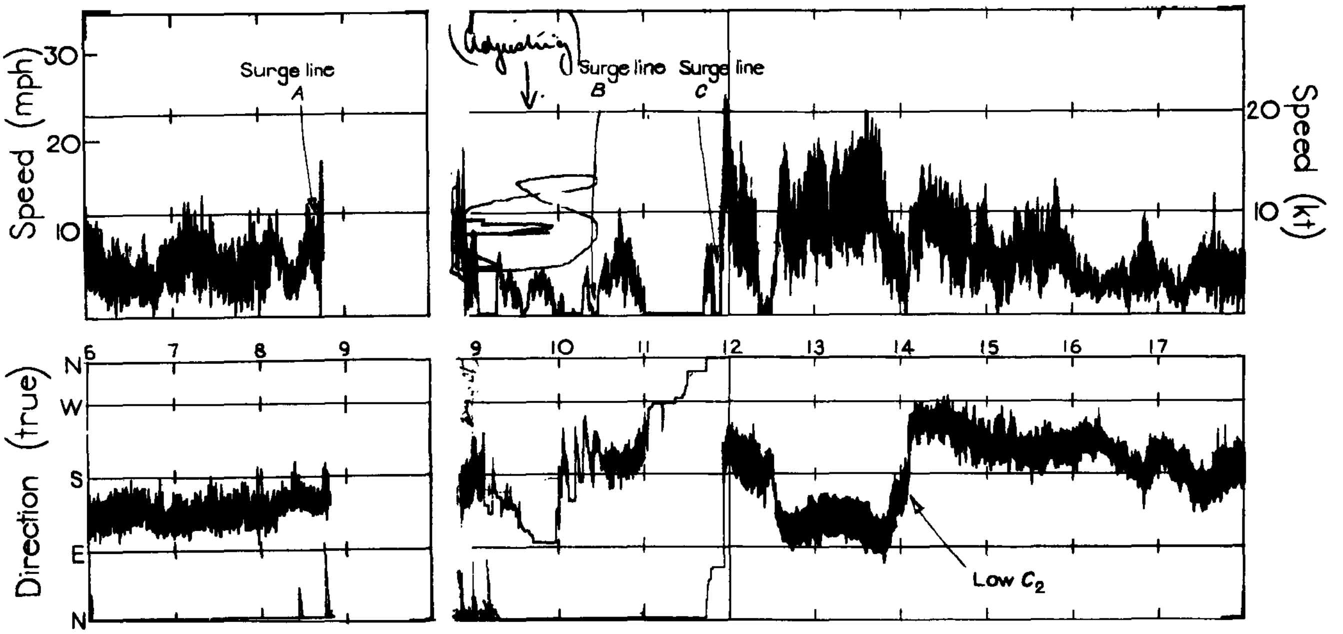


(a) Croydon (0600–0900 GMT, 5 min fast)

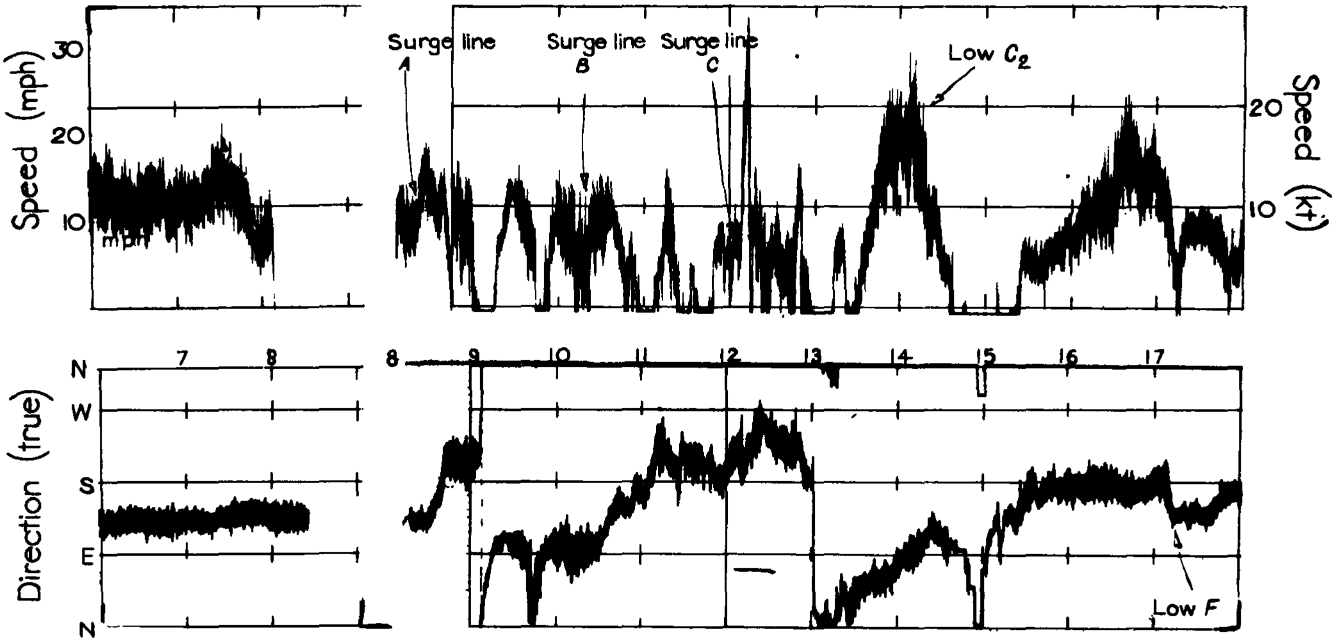


(b) East Malling

FIGURE 7—SOME EXAMPLES OF ANEMOGRAMS FOR THE PERIOD 0600 TO 1800 GMT, 28 AUGUST 1958, ILLUSTRATING DETAILED WIND STRUCTURE ACCOMPANYING THE MESO-SYSTEMS



(c) Mildenhall (5 min slow)



(d) Felixstowe (0600–0830 GMT, 10 min fast)

FIGURE 7—SOME EXAMPLES OF ANEMOGRAMS FOR THE PERIOD 0600 TO 1800 GMT, 28 AUGUST 1958 (continued)

2.4 *Analysis of rainfall*

Thundery rainfall is notoriously variable in its intensity, duration and amount. Although the storms under study were no exceptions, they were not notable for the amounts of rain which fell. However, since the amount of rain given by a storm at a given place depends only upon the intensity, size and speed of movement of the storm, and since these properties are the more fundamental, the meso-analysis of rainfall was concentrated upon intensity and duration at each observing station. Intensity and duration of rainfall are best measured by autographic rain-gauges. Fortunately the storms passed over a part of England where these autographic gauges are closely spaced. The network is particularly dense in and around London, as can be seen from Figure 9, where the average spacing is only a few miles. But in other parts of the network the spacing is unfortunately much larger, especially in Kent, East Anglia and the Fens. The emphasis on *intensity* and *duration* enables the space and time variations of rainfall to be easily determined. This approach differs from that commonly used in meso-synoptic analyses of storms in other parts of the world—analyses in which hourly rainfall *amounts* were used. Here, an instantaneous picture was obtained at the time of each meso-synoptic chart, and these pictures again show distinct patterns in the distribution of weather indicating once more that the randomness is largely illusory.

Two sources of rainfall data were available: synoptic reports (from about 100 stations) and hyetograms (about 170). The greater emphasis was placed upon the hyetograms, with the synoptic data taking an ancillary role. As a supplement to the latter, notes made by climatological observers and by private persons were also used. Similarly to the synoptic reports of pressure and wind, most of the rainfall reports were made hourly, on or near the hour. The hyetograms were taken from three types of autographic gauges: tilting-siphon and natural-siphon gauges, and hyetographs. Some (about 60) came from synoptic and climatological stations, but the majority (about 110) were supplied both by public bodies such as local government authorities and water boards, and by private individuals. All were daily charts, and times could be read easily to the nearest five minutes. Amounts were read to the nearest 0·1 millimetre (or to the nearest 0·002 inch, where the chart had a scale in inches). Readings were probably correct to ±5 minutes and ±0·1 millimetre.

Methods of extracting data from the hyetograms resembled those used for pressure, described in Section 2.2, and depended upon whether the hyetogram being used had time-marks or not. For each time-marked hyetogram (there were about 70 of them) the following data were extracted and placed on cards, the rainfall cards:

(i) Times of start and stop, amount and intensity of each burst of rain.

(ii) Notes on whether the start and stop were gradual or sudden.

(iii) Half-hourly values of rainfall intensity, each measured over a short period not exceeding five minutes.

With each hyetogram that had no time-marks (about 100), a time correction was made indirectly by selecting a salient feature of the rainfall trace as a " natural time-mark ". By comparing the indicated time of this feature (in most instances the start of the intense rainfall accompanying the third thunderstorm high, since this was very well marked and it occurred over a wide area) with the true time, a correction could be found which would apply to any position along the trace. The true time was found by first constructing an isochronic chart showing the time of commencement of the features being used as the natural time-mark (based upon those hyetograms which possessed time-marks) and then interpolating the true time for the place where the hyetogram without time-marks was obtained. Figure 10 is an example of such an isochronic chart, showing the time of commencement of the heavy rain accompanying the third thunderstorm high.

Since most of the hyetograms were changed daily around 0900 GMT, two charts from each station were needed for the analysis period 0600 to 1800 GMT. Either the method just described was used to correct the timing of both charts or, having corrected one, the other could be corrected by finding the (corrected) time when one chart was taken off and comparing it with the indicated time that the next one was put on. Some hyetograms without time-marks were kept on the recording gauges for more than one day. With these a single natural time-mark was clearly sufficient.

Having tabulated the hyetogram features, the following data were plotted for the meso-synoptic analysis of rainfall:

(i) Values of rainfall intensity in millimetres per hour, obtained from the rainfall cards.

(ii) Positions of points of start and stop, and values of intensity where rapid changes occurred, plotted upwind or downwind from the station according to whether the change occurred after or before the chart time, respectively. If the change took place more than 15 minutes from chart time it was not used. This was because such a change could be used on another chart, and also because 15 minutes is likely to be near the limit of time over which it is reasonable to expect little significant change in the characteristics of the rainfall whilst it is moving across the country. Indeed, during the early stages of development of a shower, rapid changes can occur in less than 15 minutes.

(iii) Intensities of rainfall, and timing, based on eye observations made at synoptic and climatological stations and by private persons.

The analysis of rainfall was completed by drawing isopleths of constant rainfall intensity—lines which may be called isallohyets—with values of 0, 1, 4 and 25 millimetres per hour. They were drawn with reference to continuity from one chart to the next. In Section 3, meso-synoptic analyses of rainfall intensity are shown at hourly intervals from 0600 to 1800 GMT.

Hail accompanied some of the storms, but the reports were so few and their timings so inadequate that it was not possible to make a separate analysis. The reports were obtained from synoptic and climatological observers, private persons and newspapers.

Photographs of radar displays were extremely useful sources of information for the meso-synoptic analysis. Indeed, the detail they showed was often too fine, being more suitable to the micro-synoptic scale. However, the positions of rain areas shown on plan position indicator (P.P.I.) displays greatly helped to confirm the rainfall analysis, and sometimes were of more direct use in regions of few rainfall reports. In this study P.P.I. photographs from the radar at East Hill, Dunstable, were available at quarter-hourly intervals from about 0745 to 1445 GMT and from 1630 to 1715 GMT. Also, tracings of the radar display at the London Forecast Office were available for irregular intervals during the morning.

A given radar set, working at a particular output, can detect precipitation only out to a certain range from the set. This range increases as the intensity of the precipitation increases so that, for example, the core of an intense rainstorm can be detected at ranges several times greater than that at which a shower of moderate intensity can be seen. Because of this, the edge of a precipitation area as shown by radar may not be the true edge but merely the range of detectability for the particular rainfall intensity occurring. Such an edge is diffuse and lacks the usually clear-cut nature of a true edge to a rain area. It follows, too, that when the core of a distant intense storm is detected, any surrounding rain of small intensity can escape detection completely. With the East Hill radar, cores of storms with rainfall rates of several inches per hour can be seen at ranges equal to the maximum for the set, 140 nautical miles, whereas rainfall of a few millimetres per hour is detectable only up to 40 or 60 nautical miles from the set. Another difficulty in using radar photographs in meso-synoptic analysis results from the attenuation of the intensity of the radar pulse as it travels through falling precipitation. This is because much of the energy of the pulse is scattered by the precipitation particles and only a small fraction of the original energy returns to the radar receiver. Attenuation increases with the intensity of the precipitation, so that an area of intense rainfall may well cast a " shadow " in which little or nothing can be seen. Obstacles near the transmitter act in the same way; they also produce a " permanent echo " which must be allowed for when interpreting radar displays.

Because of these difficulties—both variable detectability and attenuation—the patterns of precipitation shown by radar do not always conform to those shown by the isallohyets at ranges of 50 nautical miles or more from the radar set. In Section 3 some tracings from radar photographs are given for comparison with the rainfall analyses.

2.5 *Analysis of thunder and lightning*

The occurrence of thunder and lightning was not recorded autographically. Consequently, analyses of these two elements were based solely upon ear and eye observations. Several sources of data were used: synoptic and climatological stations, volunteer observers in a network organized by the Electrical Research Association Laboratory, private persons, and newspapers. Figure 11 shows the places where observations were made. From some only rough notes were available, but from most a continuous watch was kept throughout the analysis period. The quality of the data was very variable and the timing sometimes poor; also, because the determination of thunderstorm intensity is very subjective, the analysis is not precise. Its aim is to show:

(i) areas over which thunder could be heard at the time of analysis,

(ii) those parts of the areas where thunderstorm activity was severe.

A severe thunderstorm cannot be defined exactly, but it may be taken as one in which lightning flashes may be seen at the rate of at least two or three each minute, with the accompanying thunder almost continuous. Brilliance of lightning and loudness of thunder, as distinct from their frequency, no doubt influenced the assessment of severity, as also did the intensity of accompanying rainfall, but the confusion which may have arisen because of the latter was probably small since most of the torrential rain accompanied severe thunderstorms.

The area over which thunder may be heard from a given storm is much larger than the area of " thunder overhead ". It is not unlikely that on the day under study, thunder could be heard up to ten miles from its source, perhaps farther. Reports that thunder was particularly loud help to confirm this. The loudness may have been a consequence of the relatively high cloud-base during many of the storms. Much of the lightning was reported to be " in cloud ". However, ground strikes were plentiful as evidenced by damage to buildings, overhead power cables and to telephones. In Section 3, meso-synoptic analyses of thunder and lightning are shown at hourly intervals from 0600 to 1800 GMT. Apart from ear and eye observations of thunder and lightning, atmospherics were also used to locate some of the storm centres. Positions of sources of atmospherics have been entered on the charts using conventional symbols, where the number of feathers increases with the severity of the storm. These positions are given only to the nearest half degree of latitude and longitude, and consequently they do not always coincide with true storm centres.

2.6 *Analysis of clouds*

Even more so than for thunder and lightning, the observation of clouds is subjective, and especially is this true for the estimation of cloud heights. Because of this, no analysis of cloud height was attempted. Some measured heights of bases and tops were available from aircraft, and so were a few tops of precipitation echoes from the East Hill range height indicator (R.H.I.) radar display. The meso-synoptic analysis of clouds was confined to amount and type. On a few occasions—less than one per cent of the total—observers may have had some difficulty in correctly determining the cloud type. Comparison with neighbouring reports showed, for example, that the large amounts of dense altocumulus floccus and castellanus present were occasionally reported as stratocumulus with an estimated cloud base that was probably too low. This difficulty no doubt arose from the complex and unusual skies seen on that day.

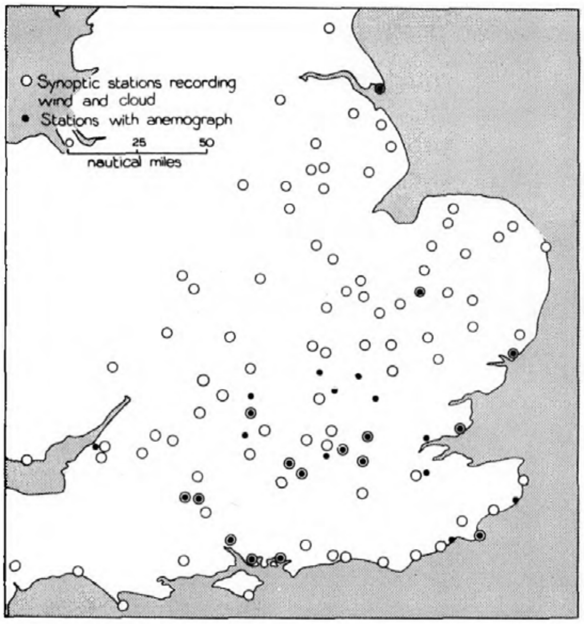

○ Synoptic stations recording wind and cloud
● Stations with anemograph
0
25
50
nautical miles

FIGURE 8—POSITIONS OF STATIONS RECORDING WIND AND CLOUD

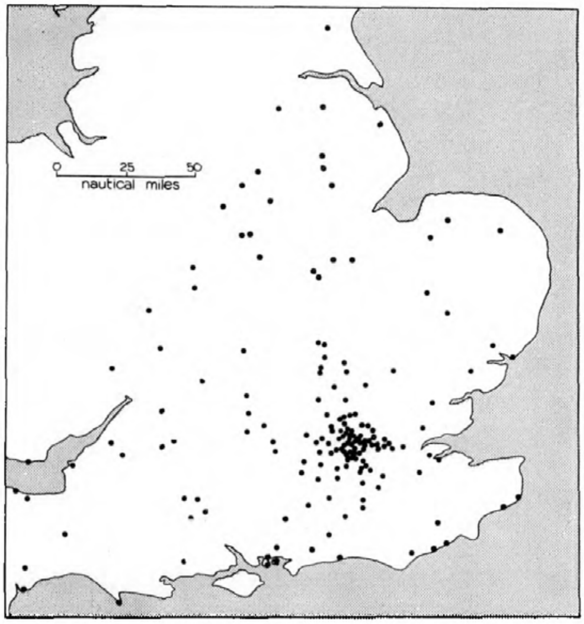

0
25
50
nautical miles

FIGURE 9— POSITIONS OF AUTOGRAPHIC RAIN -GAUGES Synoptic stations recording rain fall are the same as those shown in Figure 8

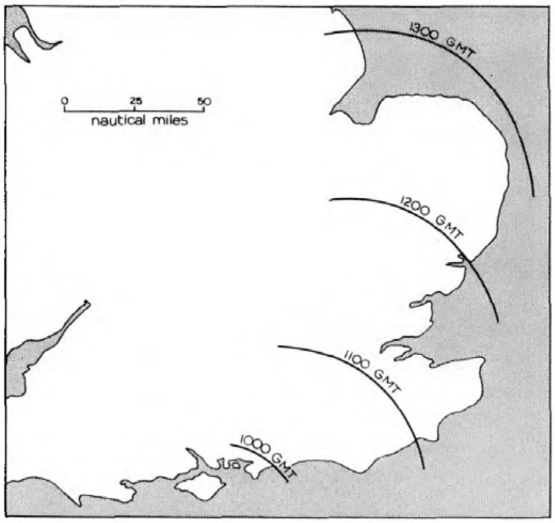

0
25
50
nautical miles
1300 GMT
1200 GMT
1100 GMT
1000 GMT

FIGURE 10—ISOCHRONIC CHART SHOWING TIME OF START OF RAIN ACCOMPANYING THE THIRD THUNDERSTORM HIGH

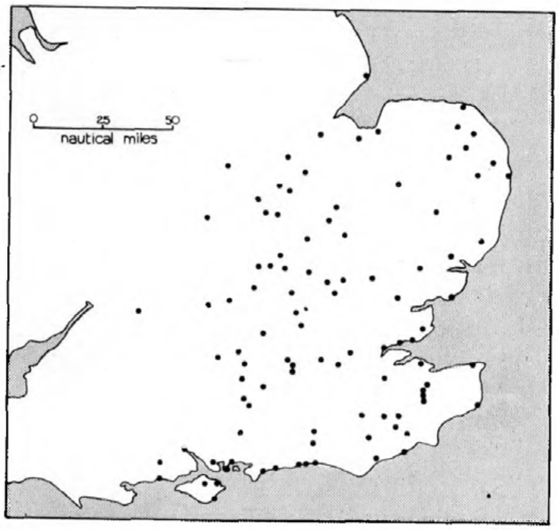

0
25
50
nautical miles

FIGURE 11—POSITIONS OF STATIONS RECORDING THUNDER AND LIGHTNING

Synoptic stations recording thunder and lightning are the same as those shown in Figure 8.

Because the cumulonimbus clouds producing the storms developed from the unstable medium clouds, for convenience the two were grouped together in the meso-analyses. These analyses were made only at hourly intervals as there were insufficient reports on the half-hours. All data were from synoptic stations, their positions being shown in Figure 8. After plotting the amounts in oktas, isonephs were drawn at two-okta intervals. Closely spaced isonephs indicate a sharp edge to a cloud sheet, the edge approximately coinciding with the four-okta isoneph. A station reporting four oktas and lying in a region of close isonephs would have one side of its sky relatively cloudfree and the opposite side covered. Such an observation, if the visibility were so good that clouds near the horizon could be seen, would be representative not of just a small area in the vicinity of the station but of an area with a radius, say, of 25 miles, or even 50 miles, because of the high altitude of the cloud.

The analysis of cloud type was more subjective. Allowing for possible errors in reporting, the following regions were identified:

(i) Altocumulus layer, or layers, with little or no evidence of vertical development, that is, species stratiformis and occasionally lenticularis.

(ii) Altocumulus layer, or layers, partly or wholly with vertical development, that is, species floccus and castellanus.

(iii) Massive medium cloud, giving thunderstorms, sometimes reported as cumulonimbus.

(iv) Altostratus or nimbostratus formed by decay of thunderstorm cloud, with or without altocumulus.

Small cumulus clouds developed at times, when there was sufficient solar heating. Stratus was sometimes present, particularly with the third thunderstorm high. High-level clouds could not be analysed because of sparsity of reports. No analyses of clouds are presented in Section 3.

§ 3—RESULTS OF MESO-SYNOPTIC ANALYSIS

3.1 *The meso-synoptic charts*

On the meso-synoptic charts (Figures 12 to 24) the following are shown:

(i) Pressure and wind. Isobars are at one-millibar intervals and are shown by continuous lines; boundaries of meso-systems are shown by pecked lines. Wind arrows are drawn conventionally, pointing in the direction from which the wind is blowing and with feathers to indicate speed to the nearest five knots. One whole feather is equivalent to ten knots and half a feather is five knots. A circle indicates a calm.

(ii) Thunder. Areas of thunder heard are roughly outlined and areas of severe thunder are shaded.

(iii) Rate of rainfall. Isallohyets are given for 0, 1, 5 and 25 millimetres per hour. Areas with a rate of rainfall greater than 25 millimetres per hour are shaded.

(iv) Radar. Areas of precipitation echoes are shaded.

3.2 *Properties of individual meso-systems*

The aim of this section is to describe the principal features of some of the meso-systems so that they may be used later to construct a composite " model " system.

Meso-system A.—The first system to cross England consisted of a thunderstorm high only—high *A*. It seemed to be merely superimposed upon the undisturbed isobars because after the high had passed the isobars returned approximately to their original orientation. It crossed the Sussex coast at about 0700 GMT, moving north-north-eastwards to lie over the sea to the north of Norfolk by 1000 GMT, and its track was from about 205° with a speed of about 70 knots. The high was generally elongated in a direction perpendicular to its motion but its axis was convex forward, indicating that the central part moved faster than its extremities. The forward edge was marked by a surge line, followed immediately by a narrow band with an intense pressure gradient, approximating to one millibar per five miles. Figure 25 shows isopleths of the pressure rise following the surge line. From it two centres in the high are apparent but the eastern centre is by far the more important. It is possible that other minor centres were also present but their small size and the relatively coarse spacing of the barograph stations made their detection impossible. The main centre reached its maximum amplitude over Essex at about 0815 GMT with a rise approaching three millibars, and thereafter it slowly decayed. By extrapolating the isopleths upstream an approximate position for the origin of the high can be deduced, and it shows that the maximum intensity was reached after about two hours. The variation of the magnitude of the rise along the line OA in Figure 25 is shown in Figure 28(a) which clearly indicates the rate of growth of the high. Throughout its life the centre of the high lay just behind the leading part of the surge line. Winds seldom exceeded 10 knots during the passing of the high. Ahead of the surge line they were light, from a south-easterly point. After the surge line a temporary increase in speed was commonly observed to build up over a period of 10 or 15 minutes, and the direction was approximately perpendicular to the isobars in the region of large pressure gradient just behind the surge line. Gusts of 15 to 20 knots were recorded in this region near the track of the centre. Subsequent wind changes depended upon the track of the centre relative to the point of observation. Anemograms showed that the wind backed to an easterly point if the centre passed to the east, but a veer to a south-westerly point occurred if it passed to the west. In most places speeds were a few knots only, and well behind the axis of the high, calms or light and variable winds were common.

Rainfall reports were not really representative because the observing stations were too widely spaced. Radar gave a much better indication of the rainfall pattern, but unfortunately no radar data were available at 0700 GMT whilst the data for 0800 GMT were less detailed than for later hours. Using the rainfall and radar observations, three regions may be distinguished. Firstly, and most extensive, an area of numerous echoes was lying in the same region as was occupied by the high. Some of these echoes were separate and small with diameters of only one or two miles, whilst others had diameters exceeding five miles, and many were joined into irregular groups. Secondly, a few isolated echoes were found ahead of the surge line, for example, near Oxford and St. Albans at 0730, near Colchester at 0800 and over Lincolnshire at 0900 GMT. These small storms had short lives in the order of half an hour only. Thirdly, several groups of echoes developed well in the rear of the high. These echoes were arranged in rows lying roughly north-east to south-west.

During the first hour or two in the life of the system the radar echoes were mostly clear-cut and intense, showing that the storms were new, and this was many times confirmed by surface rainfall reports which showed that the bursts of rain usually began and ended suddenly and that intensities were large. By 0900 GMT the rain areas from individual storms had begun to merge into a more continuous zone but still of variable intensity. Most of the rainstorms were associated with the high, but others in its rear had little or no effect on surface pressure. The most intense storms lay nearest the track of the centre of the high, whilst hail fell at Southend and Shoeburyness.

Although the rain areas under study are meso-systems it will not be amiss here to briefly consider the initial small-scale systems from which they develop. This cannot be done with autographic data unless the instruments form a very dense network with a spacing of, say, one mile. However, radar is ideal for this purpose as it easily shows rain cells with diameters as small as one mile. Very conveniently in the rear of meso-system A, a large number of new cells were developing well within the range of the radar. Figure 29 shows the evolution of echoes from these cells between 0748 and 0900 GMT; in the latter maps, the widespread echoes from the main area rain have been omitted.

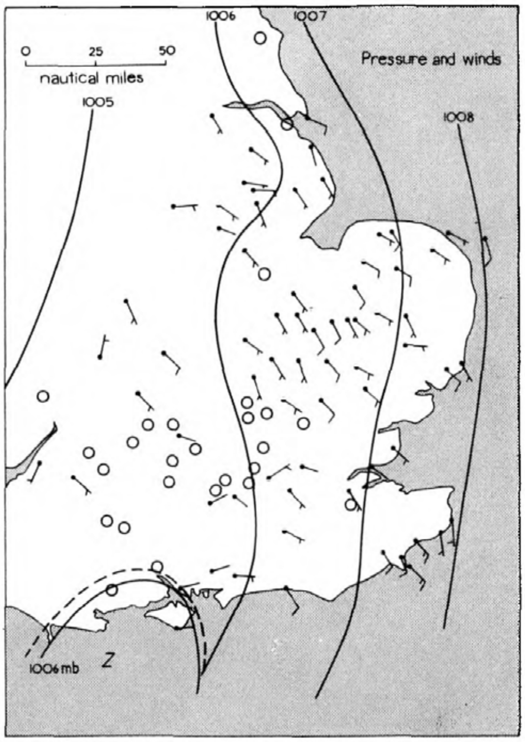

1006
1007
0 25 50
nautical miles
Pressure and winds
1005
1008
1006mb
Z

FIGURE 12—CHART FOR 0600 GMT
No thunder heard, no rain recorded, no radar data available.

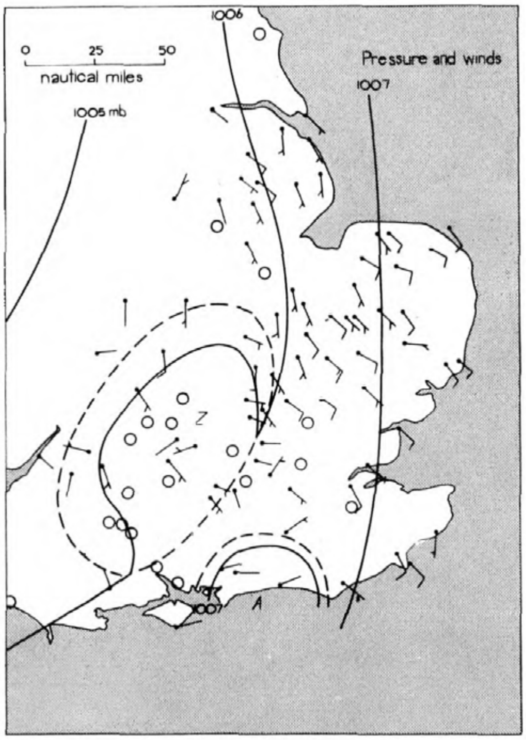

1006
0 25 50
nautical miles
Pressure and winds
1007
1005 mb
Z
1007
A

FIGURE 13—CHART FOR 0700 GMT

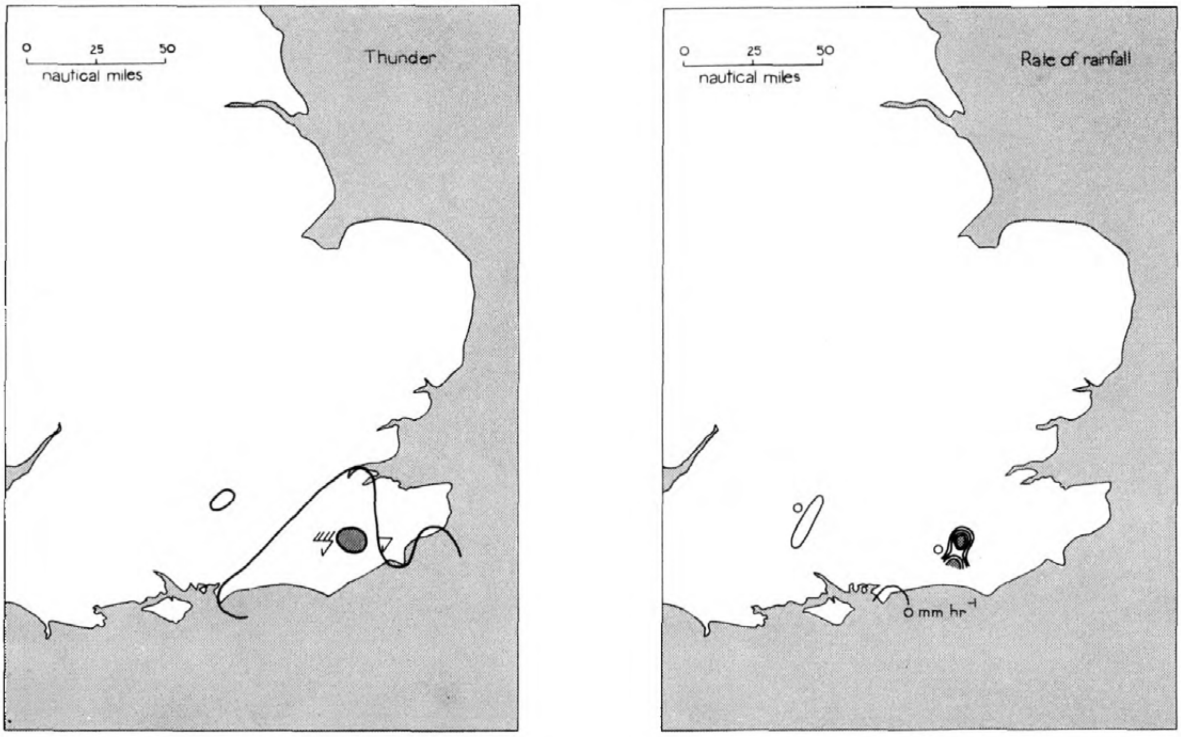

0 25 50
nautical miles
Thunder
0 25 50
nautical miles
Rate of rainfall
0 mm hr⁻¹

FIGURE 13 (continued)—CHARTS FOR 0700 GMT
No radar data available.

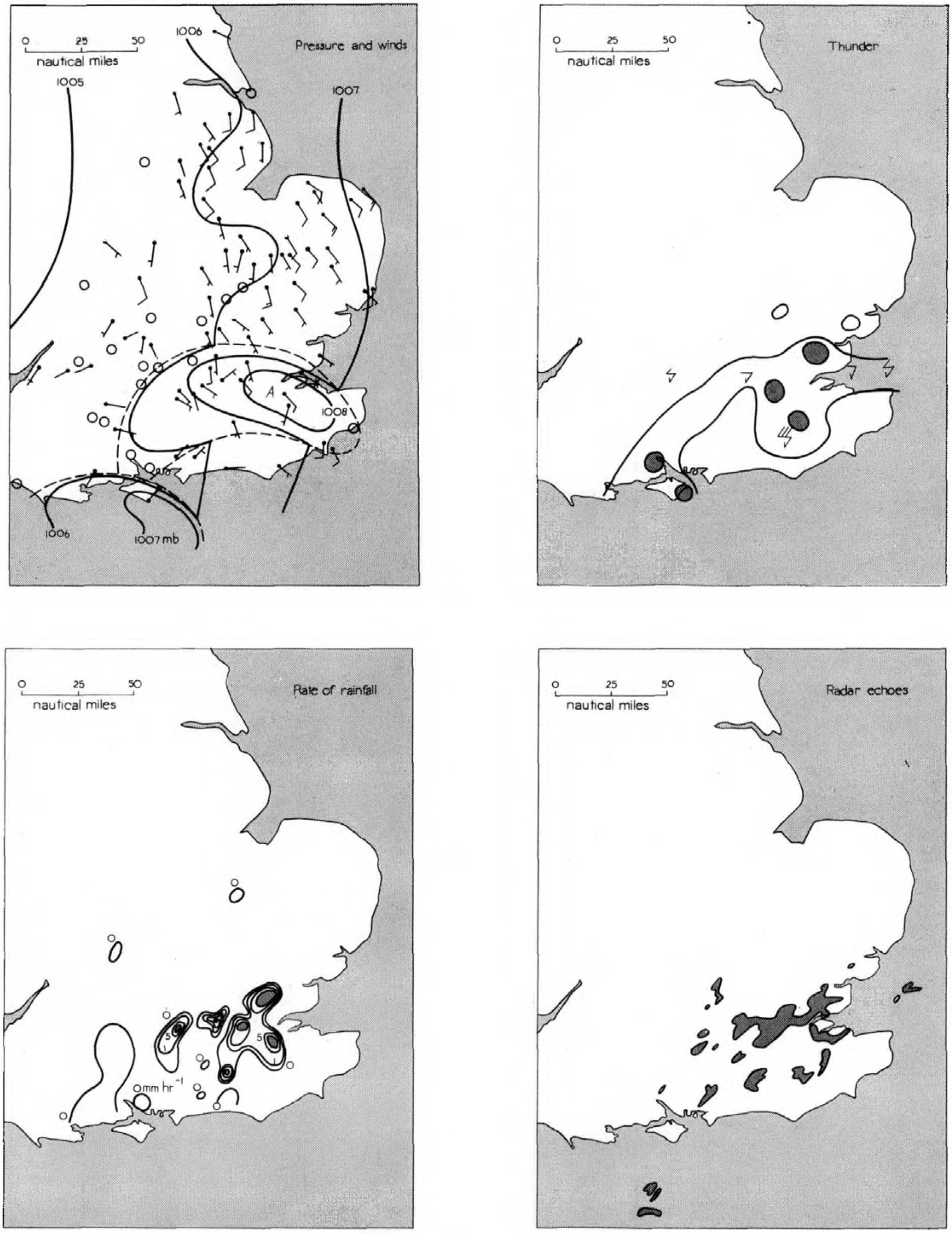

0 25 50
nautical miles
Pressure and winds
1005
1006
1007
1008
A
1006
1007 mb
Thunder
Rate of rainfall
5
0 mm hr⁻¹
Radar echoes

FIGURE 14—CHARTS FOR 0800 GMT

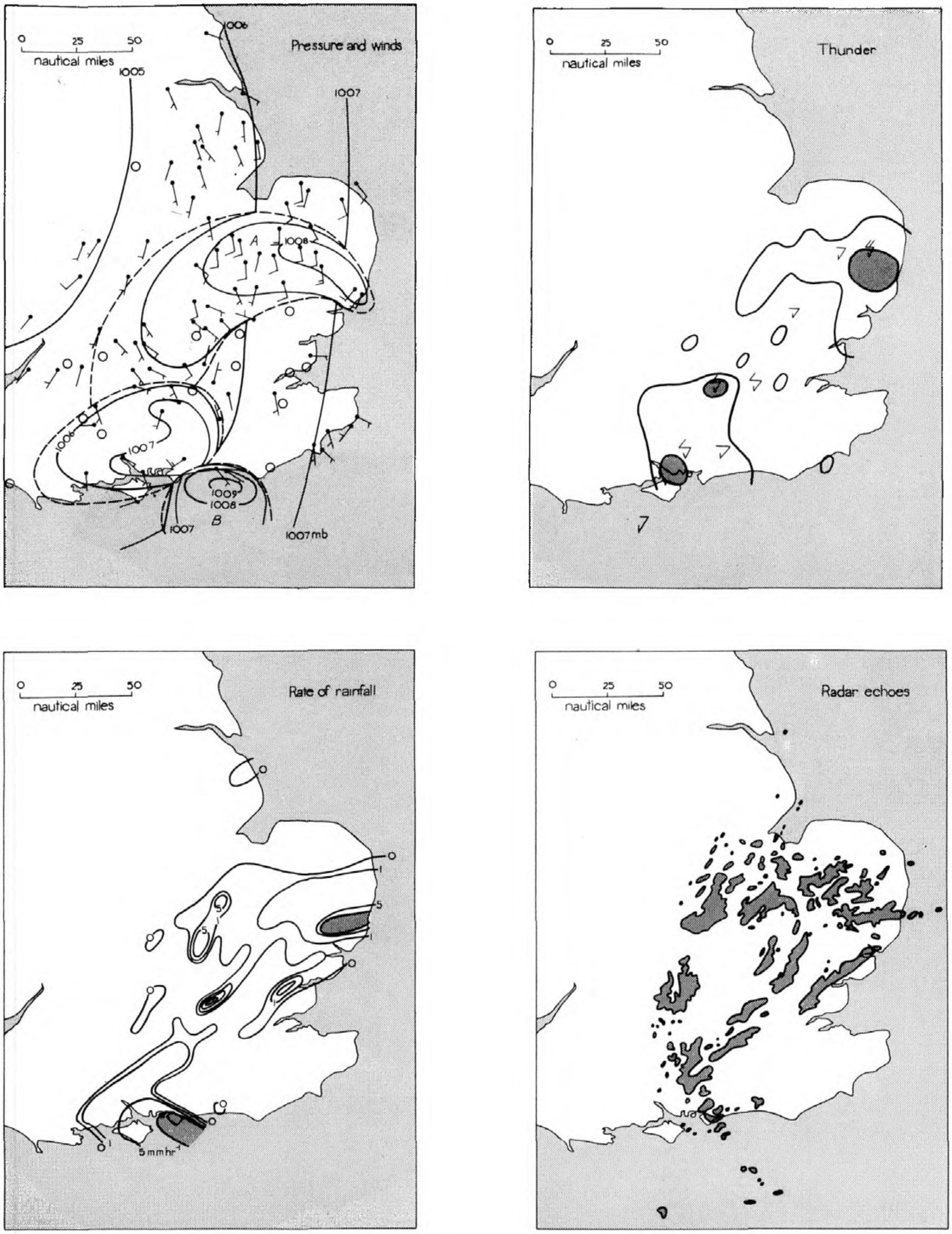

0 25 50
nautical miles
Pressure and winds
1006
1005
1007
A
1008
1006
1007
1009
1008
B
1007
1007mb
Thunder
Rate of rainfall
0
1
5
5 mm hr⁻¹
Radar echoes

FIGURE 15—CHARTS FOR 0900 GMT

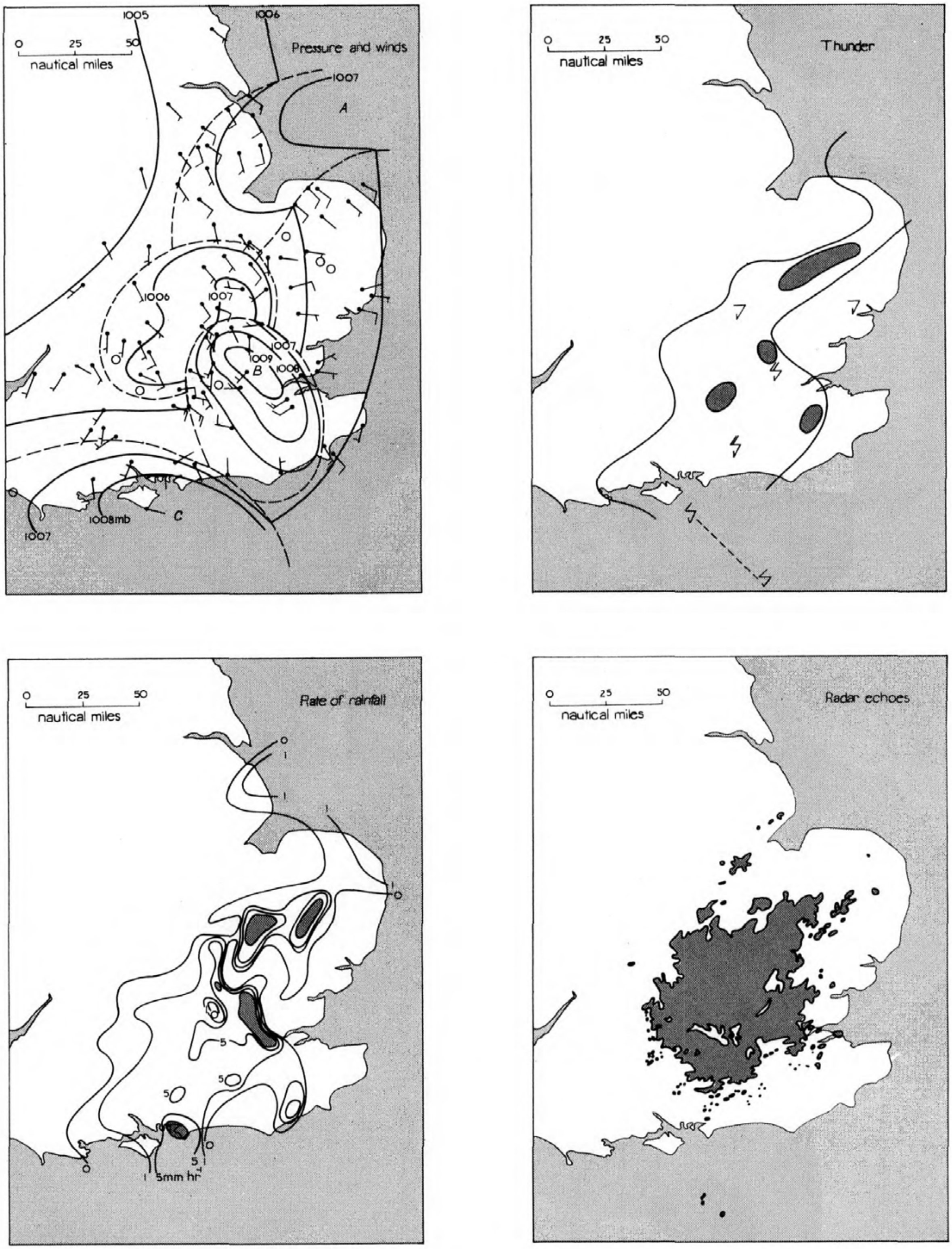

0 25 50
nautical miles
Pressure and winds
1005
1006
1007
A
1006
1007
1007
1009
B
1008
1008mb
C
1007
0 25 50
nautical miles
Thunder
0 25 50
nautical miles
Rate of rainfall
0
1
1
1
1
0
5
5
5
0
1
5mm hr⁻¹
5
0
0
0 25 50
nautical miles
Radar echoes

FIGURE 16—CHARTS FOR 1000 GMT

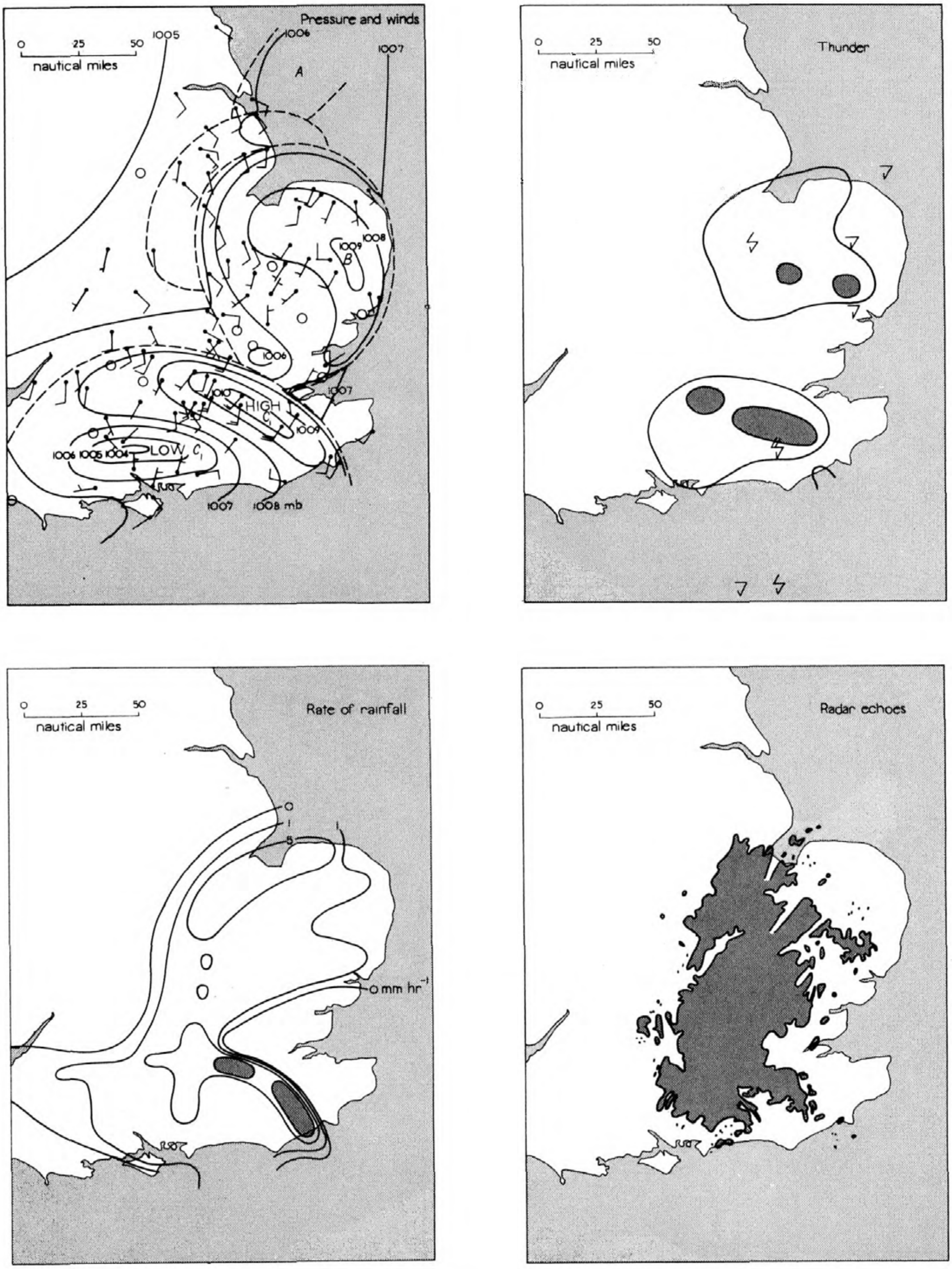

Pressure and winds
0
25
50
nautical miles
1005
1006
1007
A
1008
1009
B
1006
1010
HIGH
C_1
1007
1009
1006 1005 1004
LOW
C_1
1007
1008 mb
Thunder
0
25
50
nautical miles
Rate of rainfall
0
25
50
nautical miles
0
1
5
1
0
0
0 mm hr^{-1}
Radar echoes
0
25
50
nautical miles

FIGURE 17—CHARTS FOR 1100 GMT

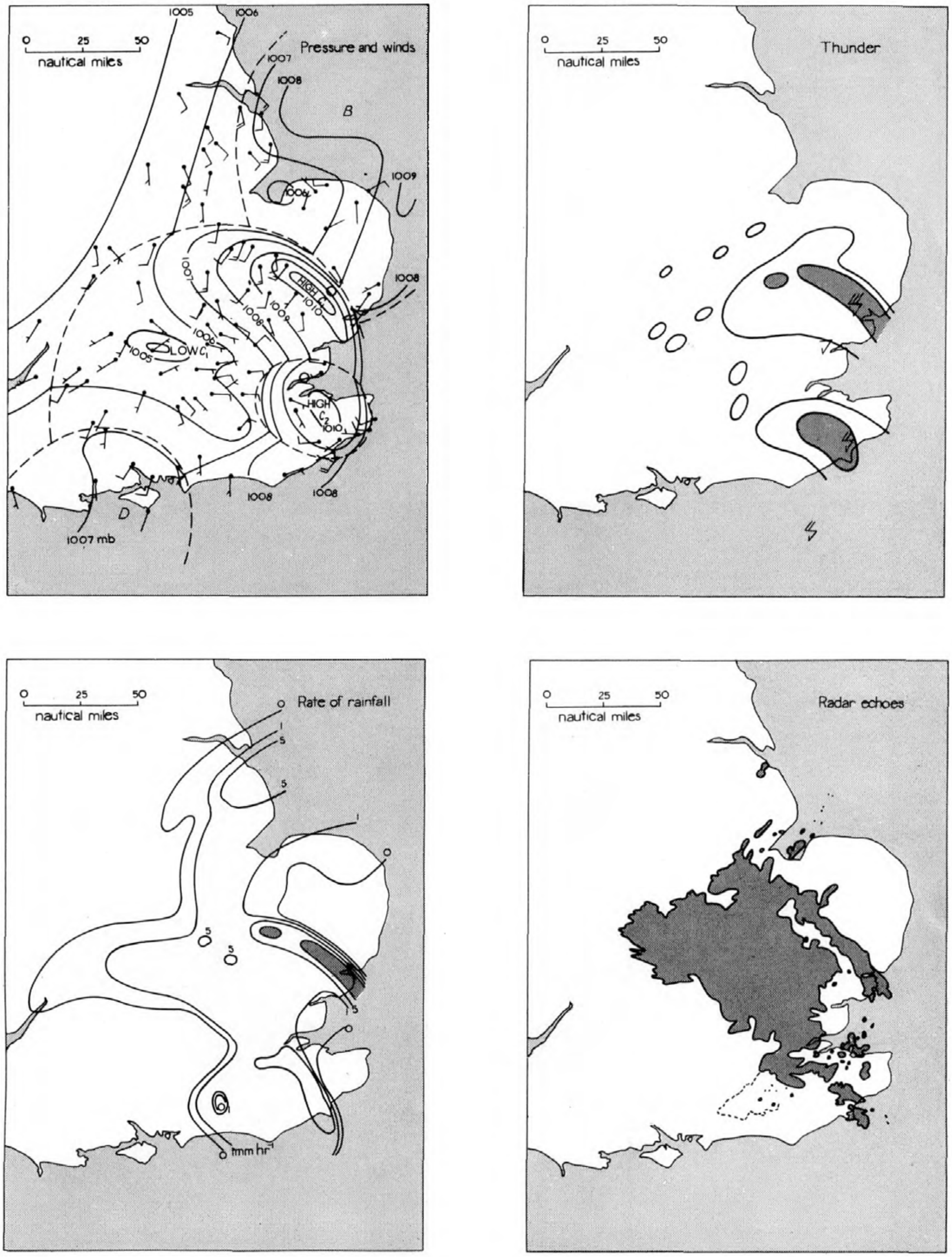

Pressure and winds
0 25 50
nautical miles
1005
1006
1007
1008
1009
B
1006
1008
HIGH C_2
1010
1007
1008
1009
LOW C_1
1005
1006
HIGH C_2
1010
1008
1008
D
1007 mb
Thunder
0 25 50
nautical miles
Rate of rainfall
0 25 50
nautical miles
0
1
5
5
1
0
5
5
5
0
0 mm hr⁻¹
Radar echoes
0 25 50
nautical miles

FIGURE 18—CHARTS FOR 1200 GMT

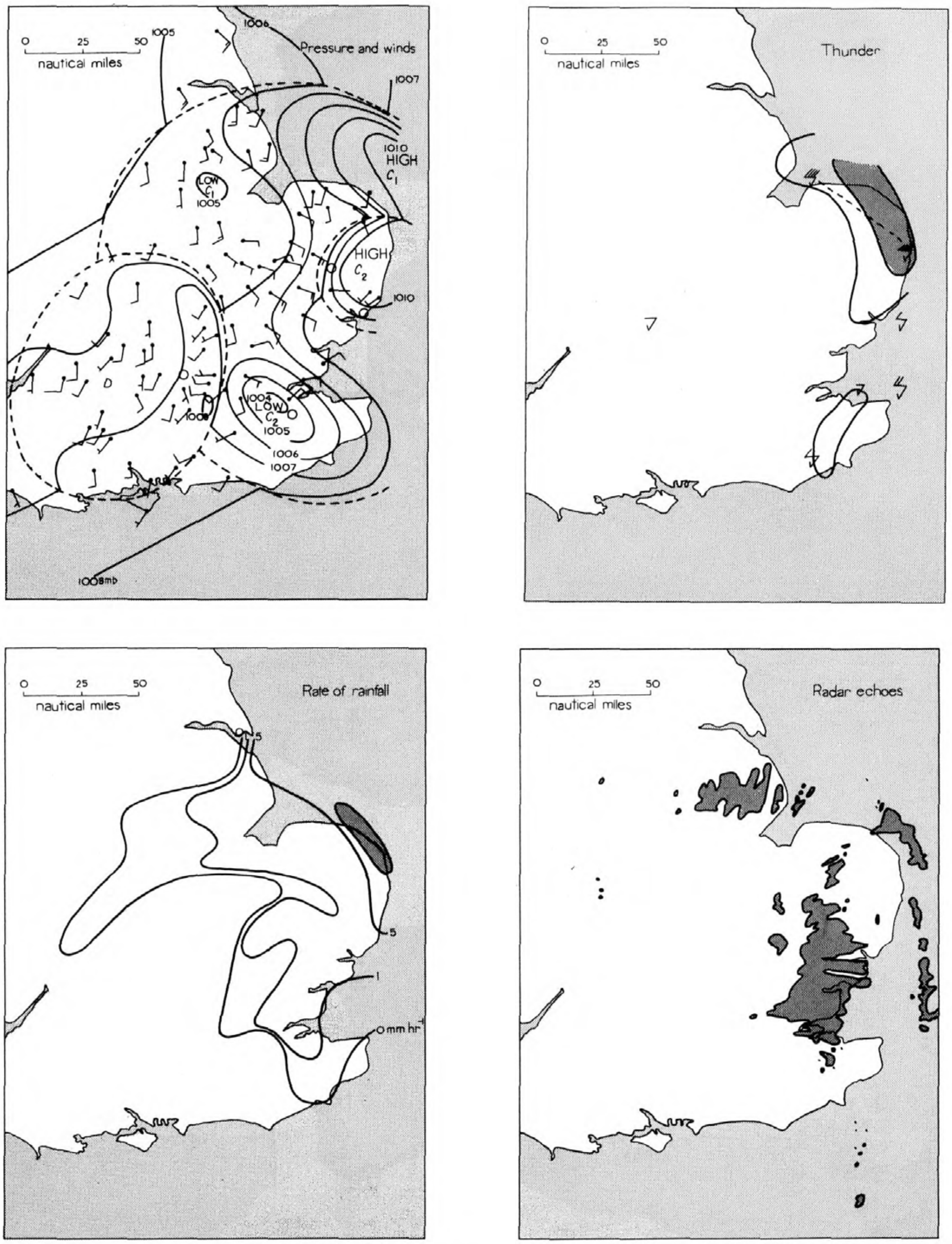

0 25 50
nautical miles
Pressure and winds
1005
1006
1007
1010
HIGH
C_1
LOW
C_1
1005
HIGH
C_2
1010
D
1004
LOW
C_2
1005
1006
1007
1008
1008mb
Thunder
Rate of rainfall
5
5
1
0 mm hr⁻¹
Radar echoes

FIGURE 19—CHARTS FOR 1300 GMT

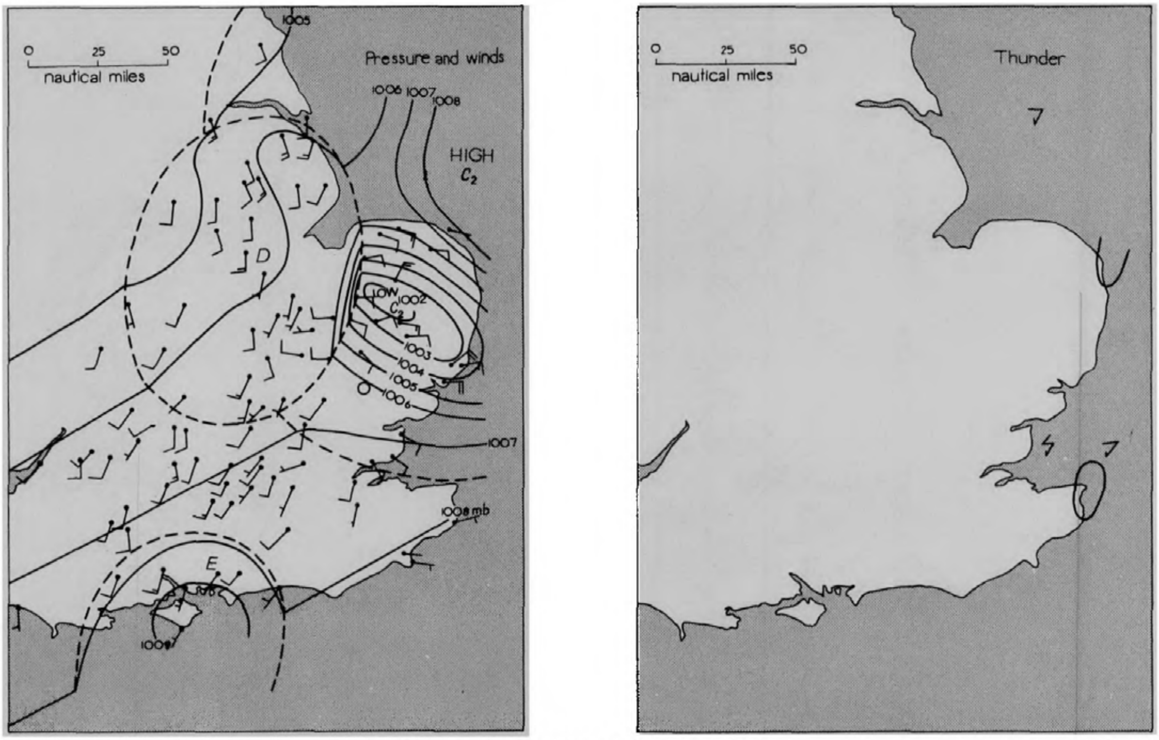

0 25 50
nautical miles
Pressure and winds
1005
1006 1007 1008
HIGH
C2
D
LOW
C2
1002
1003
1004
1005
1006
1007
1008 mb
E
1006
1007
0 25 50
nautical miles
Thunder

FIGURE 20—CHARTS FOR 1400 GMT

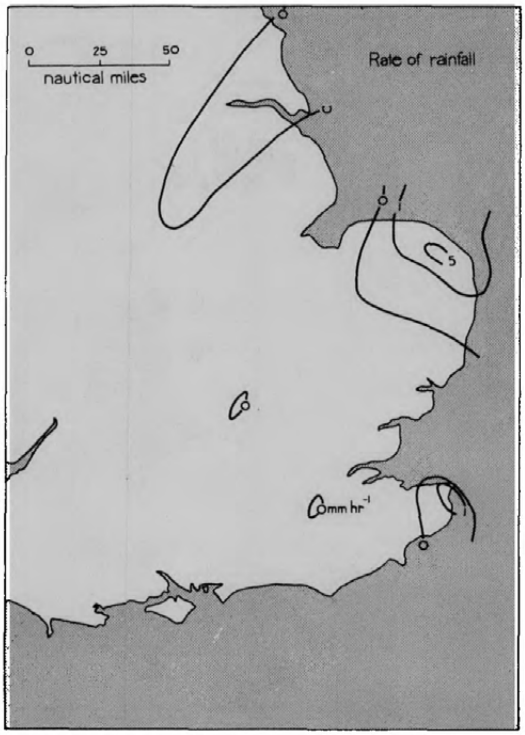

0 25 50
nautical miles
Rate of rainfall
0
5
0 mm hr-1

FIGURE 20 (continued)—CHART FOR 1400 GMT
No radar echoes seen.

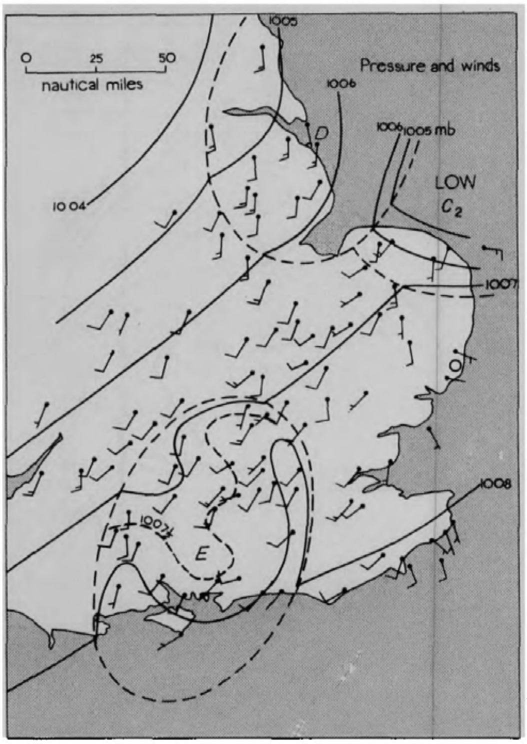

0 25 50
nautical miles
1005
Pressure and winds
1006
1006 1005 mb
LOW
C2
1004
D
1007
1008
1007
E

FIGURE 21—CHART FOR 1500 GMT
No thunder heard, no rain recorded, no radar data available.

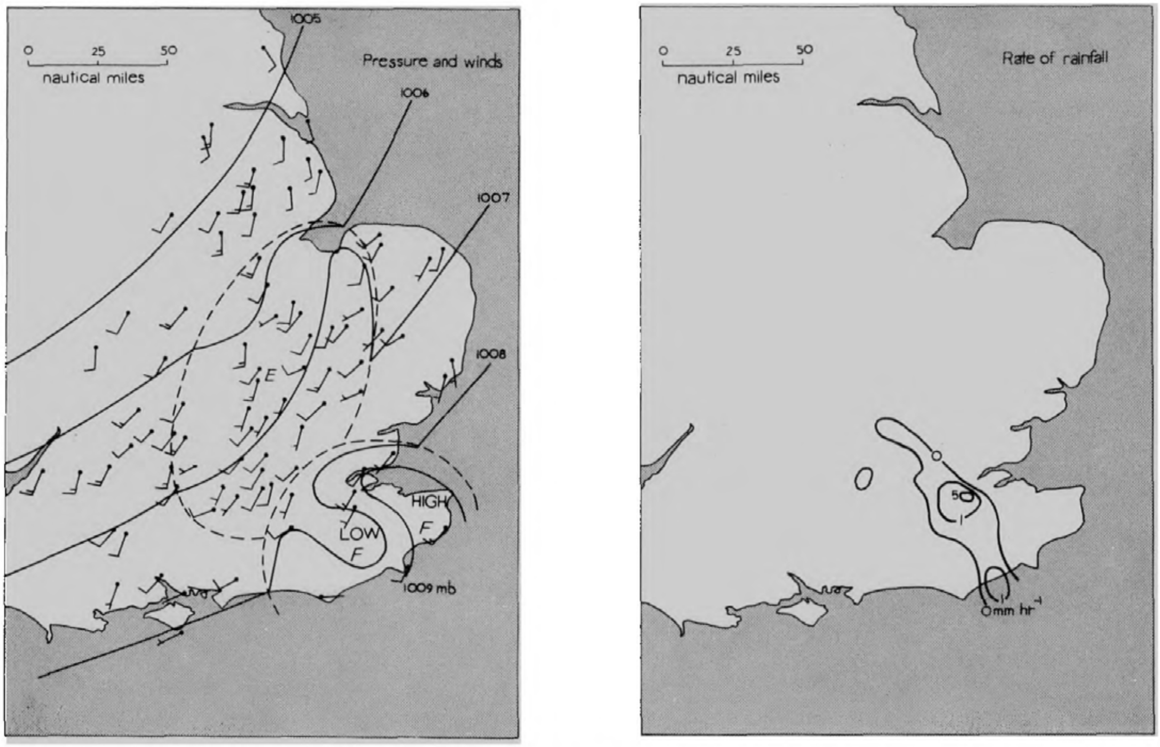

0 25 50
nautical miles
Pressure and winds
1005
1006
1007
1008
E
HIGH
LOW
F
F
1009 mb
0 25 50
nautical miles
Rate of rainfall
0
5
1
1
0 mm hr^{-1}

FIGURE 22—CHARTS FOR 1600 GMT No thunder heard, no radar data available.

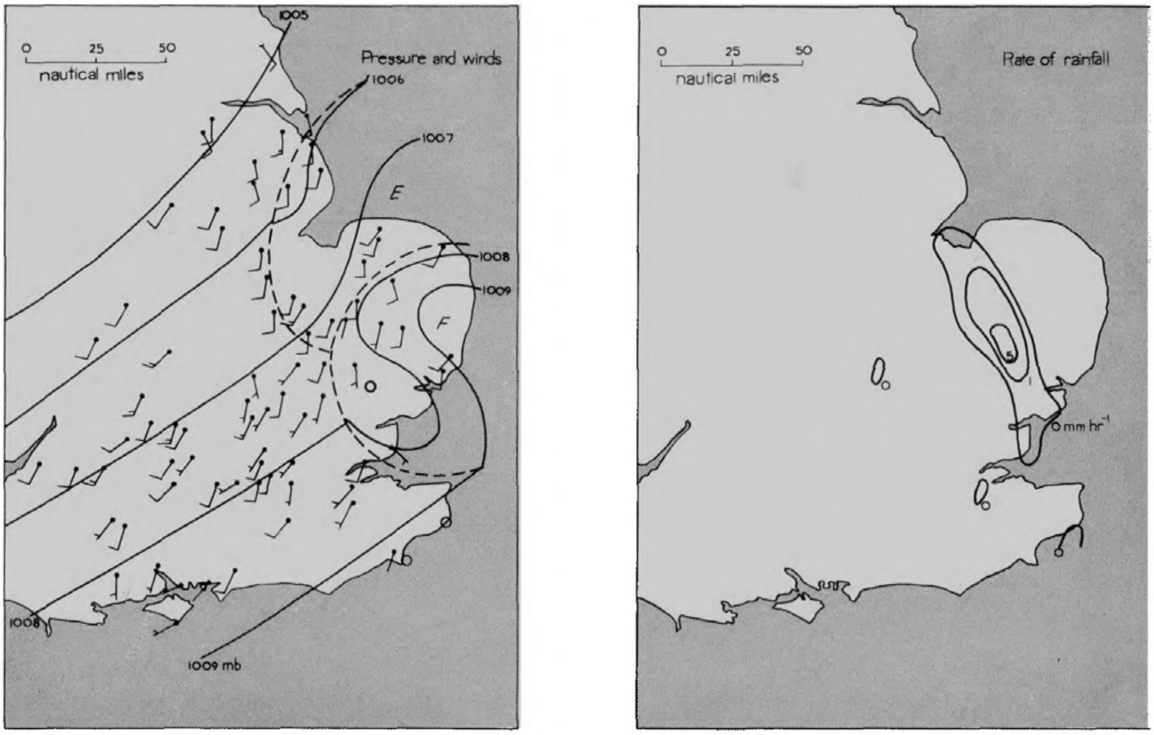

0 25 50
nautical miles
Pressure and winds
1005
1006
1007
E
1008
1009
F
0
1008
1009 mb
0 25 50
nautical miles
Rate of rainfall
0
0
5
1
0 mm hr^{-1}

FIGURE 23—CHARTS FOR 1700 GMT

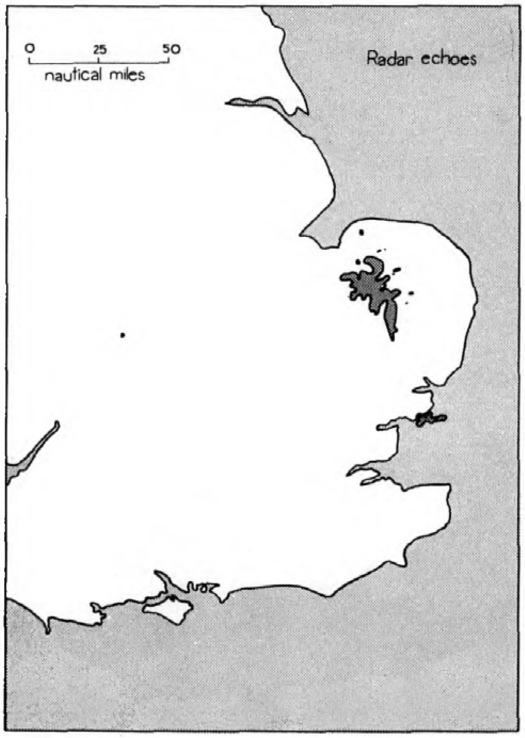

0 25 50
nautical miles
Radar echoes

FIGURE 23 (continued)—CHART FOR 1700 GMT
No thunder heard.

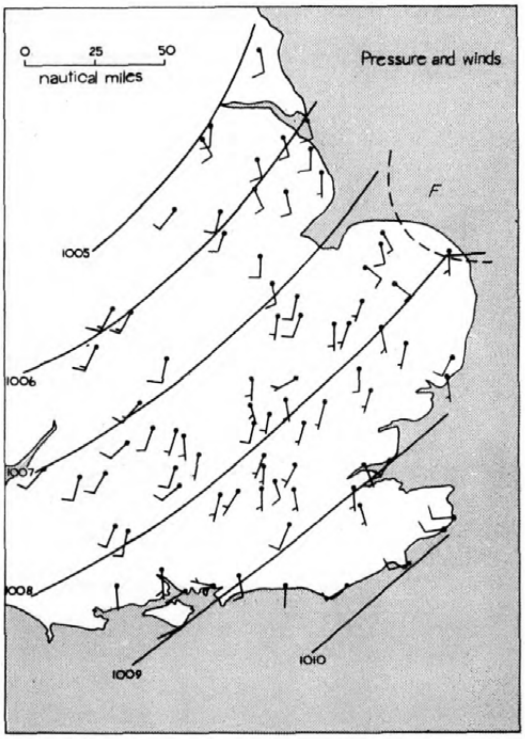

0 25 50
nautical miles
Pressure and winds
F
1005
1006
1007
1008
1009
1010

FIGURE 24—CHARTS FOR 1800 GMT

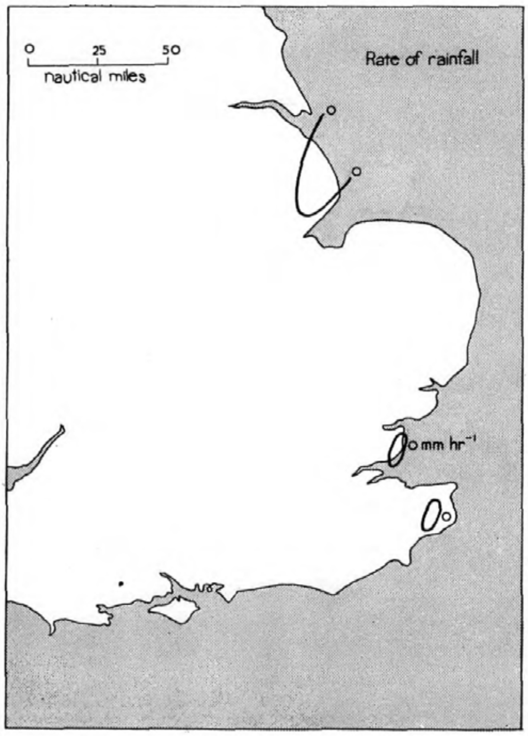

0 25 50
nautical miles
Rate of rainfall
0
0
0 mm hr^{-1}
0
0

FIGURE 24 (continued)—CHARTS FOR 1800 GMT
No thunder heard, no radar data available.

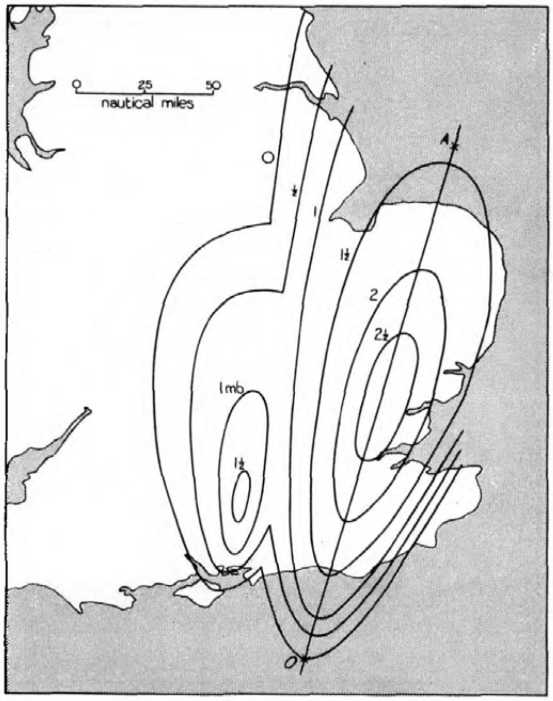

0 25 50
nautical miles
A
0
½
1
1½
2
2½
1 mb
1½
A'

FIGURE 25—ISOPLETHS OF PRESSURE RISE FOLLOWING SURGE LINE OF SYSTEM *A*

At 0748 GMT five storms lay in the rear of the meso-system; they are marked *A*, *B*, *C*, *D* and *E*. Four others, *F*, *G*, *H* and *I*, formed part of the main rain system. The five moved steadily across country, maintaining a remarkably uniform orientation. Some of them had irregular and changing shapes showing that each consisted of a small cluster of cells with short lives, new cells forming as old ones decayed. By 0830 GMT the new storms *J* and *K*, lying between the other two sets and first noted at 0815 GMT, had themselves grown into clusters. Whereas storm *J* developed into a row of cells (orientated differently from the line *A* to *E*), *K* appeared as an irregular group. Another storm, *L*, had developed south of *C*, and by 0845 GMT this storm was accompanied by others, *Q*, *R*, *S*, *T* and *U*, rapidly forming in the area between *A* to *E* and meso-system *B*, some of whose centres are shown by *M*, *N*, *O* and *P*. Many of these storms rapidly grew and fused by 0900 GMT, but some of the growth may be apparent only, being attributable to the storms being more easily detected as they approached the radar station.

A feature of these storms was their great tendency to form in rows. Although these rows had several orientations, no obvious relationship to the wind flow could be seen, and their orientation remains unexplained. Whereas individual cells probably had short lives in the order of half an hour, the small clusters were more persistent; for example, storms *A*, *B*, *C*, *D* and *E* were still detectable as parts of complex echoes after more than an hour.

Small distortions of the radar presentation made it impossible to pinpoint the location of individual echoes with sufficient accuracy to enable the rainfall from them to be found from the rain-gauge records. However, there seemed to be several instances where echoes showed storms passing over gauges without any rain being recorded at the ground. Most of these cells were very new and it is likely that the rain within them had not had enough time to fall to the ground. Depending upon the strength of the upcurrents within the clouds, a lag of, say, one quarter to one half of an hour is to be expected between the time when sufficient drops have formed to produce an echo and the time when the first drops reach the ground. Figure 30 shows the approximate total rainfall produced by meso-system *A*, based on both gauge records and the movement of radar echoes. The variability reflects the complex distribution of cells.

Clouds were almost entirely at medium levels and consisted of large amounts of multilayered altocumulus floccus and castellanus, with the lowest base at about three kilometres. Aircraft reports and vertical cross-sections obtained by radar showed that tops occasionally exceeded 12 kilometres. Figure 31 shows two range height indicator radar cross-sections through the system.

Thunder was widespread but of variable intensity. Only a rough pattern of distribution could be obtained, but the most severe centres seemed to accompany the most intense rainstorms. The thunder over eastern Sussex around 0700 GMT was ahead of the surge line and dissipated as it moved northwards. It was accompanied by only a few outbreaks of rain and probably represented small storms at medium levels which failed to develop further. Some isolated claps also accompanied other storms ahead of the surge line. The severe storms over west Suffolk and south Cambridgeshire at 1000 GMT had been developing behind the meso-high since its first appearance on radar at 0845 GMT but it produced no significant effect on surface pressure even after more than one hour of active life.

Meso-system B.—Whilst high *A* was crossing London, the leading edge of a second system crossed the Isle of Wight and the coast of Dorset at about 0800 GMT. It too consisted of a thunderstorm high only—high *B*—which again seemed to be merely superimposed on the undisturbed isobars. This high also consisted of two centres with the dominant one to the east moving north-north-eastwards from Sussex to Norfolk. The second and decaying centre had a track rather more to the west—from the Isle of Wight towards Cambridgeshire—and it lay some 30 miles in advance of the main centre so that the combined surge line preceding them had a complex shape. Stations in the west of the region affected by system *B* experienced two pressure rises, one for each of the axes of the high, but those in the east had only one rise. Figure 26 shows isopleths of the pressure rise following the surge line of the easternmost centre. Its maximum amplitude was reached over eastern London at about 1000 GMT with a rise of just over four millibars. It was not possible to extrapolate the isopleths sufficiently far upstream to determine a position for the origin of the high, but it seems likely to have been in existence for at least three hours before reaching its maximum amplitude. The variation of the magnitude of the pressure rise along the line *OB* in Figure 26 is shown in Figure 28(*b*). When the main high was just beginning to decay, that is, when it was crossing East Anglia, its centre seemed to be displaced farther to the east so that it lay not behind the leading part of the surge line but some 20 miles to the right by 1100 GMT. This contrasted with the centre's position earlier in its life, and also with the position of the centre of high *A*.

The surge line marking the forward edge of the system was followed by a narrow band with an intense pressure gradient, comparable with the gradient observed for system *A*. Winds responded to the passing of the high in a way similar to that observed with system *A*. After the surge line a temporary increase in speed to 10 or 15 knots was common over a period of 10 to 15 minutes, with gusts up to 20 or 25 knots in places. The wind direction was approximately perpendicular to the isobars. Behind the axis of the high, speeds decreased to generally less than 10 knots and, just as was observed with high *A*, the direction changed according to the track of the centre relative to the point of observation—it backed to the east if the centre passed to the east, but veered to the west or south-west if the centre passed to the west. This contrast in changes of wind direction was well shown by the anemograms from the west and east of London respectively.

Although rainfall reports were again not really representative, nevertheless they gave a rough picture of the rainfall pattern, corresponding quite well to the pattern shown by radar. Two main régimes could be distinguished. Firstly, a belt of intense cores was roughly aligned north-west to south-east and accompanying the central parts of the main high centre. This belt was entering west Sussex at 0900 GMT when it gave a rainfall rate exceeding one inch per hour, and by 1000 GMT it was crossing London still giving intense falls, but by 1100 GMT it was decaying rapidly over Suffolk. Hail fell as the belt passed over Gatwick. The second régime consisted of an area of rain some 50 to 70 miles broad with its forward edge roughly corresponding to the position of the surge line. This meant that its westernmost part, which lagged behind the apparently faster-moving central part, was joined to the main area of the following system *C*. Consequently, some stations in the west of the area affected by both systems *B* and *C* had rain lasting for several hours, whereas those in the east had a break between the rain areas of the two systems. The rain in this broad area had a variable intensity, mostly two to four millimetres per hour, and was very probably formed by the fusion of remains of old storm cells which had been active during the earlier life of the system. The radar echo from this rain showed a distinct " bright band ", indicating that it was formed by melting of snow. At 1000 GMT the radar did not show the real extent of the rain area because the southern edge was too weak to be detected. It also failed to distinguish between the row of intense cells and the broad rain area, but earlier, at 0900 GMT, only the cores of these cells were detectable. The only new, sharply defined, growing cells at 1000 GMT seemed to be at the right-hand end of the belt of intense rainfall around the Thames estuary, but the evidence is not clear, and judging by the intensity of the rain in the belt across London it is possible that new cells were actively growing there too. By 1100 GMT, after decay of the high had started, no intense cells remained over land.

Clouds were again almost entirely at medium levels, as in system *A*, but this time much stratiform cloud was also present, both altostratus and nimbostratus. These were probably the result of decaying storm centres combining together to cover the sky completely. In places much altocumulus floccus and castellanus were also present, including " medium-level cumulonimbus ". Figure 32 shows a range height indicator radar cross-section through the system at 1022 GMT where only diffuse tops can be seen at about nine to ten kilometres; no hard-edged cells are evident.

Thunder was widespread but mostly slight. A few severe centres were present however. In particular two centres associated with the western high were of interest. One passed over the Southampton area about 0800 GMT and struck overhead power lines so that much of the Isle of Wight was without electricity for about one hour. The television and VHF transmitters at Rowridge were put out of action. Another severe storm over the eastern part of the Isle of Wight at much the same time, accompanied by very heavy rain (and also hail at Ventnor), produced near darkness and also damage by lightning.

Meso-system C.—By 1000 GMT the leading edge of the third and most interesting system had already crossed the south coast of England from Dorset to Sussex. As it moved north-north-eastwards its structure proved to be complex, consisting not of a thunderstorm high alone as with systems A and B but of two highs and two lows with subsidiary troughs and ridges. Behind its extensive surge line was an elongated high with its axis approximately perpendicular to its direction of motion but also slightly convex forward showing that the central part moved faster than its extremities. The pressure gradient in a narrow band just behind the surge line was particularly large and difficult to display accurately on the meso-synoptic maps; in places it approached one millibar per mile. Figure 27 shows isopleths of the pressure rise following the surge line. A maximum amplitude of about five millibars was attained at about 1100 GMT over south-eastern London, followed by a decline as the high moved into East Anglia. However, over Norfolk there was evidence of renewed intensification with the amplitude again reaching about four millibars around 1230 GMT. The high following the surge line was clearly already many hours old when it first reached the Sussex coast because even then the amplitude of the pressure rise exceeded four millibars. This high, which we may call high C_1, was followed by another smaller high, C_2, whose track lay more to the east, from Kent to east Suffolk and then to the extreme east of Norfolk. High C_2 appeared to combine with high C_1 by 1300 GMT so that over the east of East Anglia the two together gave a prolonged pressure rise lasting about one hour.

In the rear of the two high centres pressure fell rapidly, often to less than the undisturbed value. This shows on the meso-synoptic maps as a complex " wake trough " with two low centres. The first low, low C_1, crossed the English coast just west of the Isle of Wight at about 1045 GMT and moved towards Lincolnshire on a track slightly east of north. This track was well to the left (west) of the track of high C_1 and, indeed, the two centres gradually diverged as they moved across England so that by 1300 GMT, as is shown in Figure 33, they were about 100 miles apart. The second low, low C_2, crossed the coast just west of Beachy Head at about 1230 GMT and moved to mid-Norfolk by 1400 GMT on a track a little east of north—from 195° at about 70 knots. This track was offset to the west of high C_2 and again diverged slightly from it. Its central pressure continued to fall slowly as it crossed East Anglia, reaching about 1001·5 millibars over mid-Norfolk. Because low C_2 followed within about one hour and a half behind high C_1, some large and rapid pressure changes were observed at stations affected by both of them. Figure 34 shows isopleths of the pressure change between high C_1 and low C_2. Pressure gradients around low C_2 were comparable in size to those found with any of the meso-highs.

The response of surface winds to the changing pressure gradients of system C were well defined and very interesting. Behind the surge line, winds blew perpendicular to the isobars away from the axis of the high, that is, from between south and south-west, but speeds seldom exceeded 20 knots; gusts of 25 to 30 knots were observed near the track of the high's centre. Wind flow across the isobars was also well established in the rear of the highs, thus producing three localized wind regions:

(i) In the west of the area affected by system C, where only one high (C_1) passed over, the wind backed rapidly to between east and north-east, with speeds of about five knots.

(ii) Farther to the east but still to the west of the combined highs C_1 and C_2, the wind backed only as far as between east and south-east, with speeds of 10 to 15 knots.

(iii) Farther east still, to the east of the highs, winds veered to west, at five to ten knots.

The backing to the directions of régime (i) meant that an almost complete reversal took place compared with the wind direction just behind the surge line. However, the line separating these two streams did not coincide with the axis of high C_1, that is, the wind did not reverse in the same place that the pressure gradient reversed, but in its rear. In all cases, the change of direction as the highs passed was not sudden: although rapid, it was remarkably smooth. Combining these observations of wind directions around the highs C_1 and C_2, it is clear that there was a very pronounced flow outwards from the centres of the highs. Correspondingly, around the low centres C_1 and C_2 there was strong flow inwards towards their centres, and this was particularly well shown by low C_2. Ahead of low C_2, winds blew across the isobars from between east and north-east with speeds of 15 to 20 knots, and gusts to 30 knots near the centre. Behind the low, directions were from between south-west and west with speeds of about 10 knots. The reversal was rapid but smooth and it took place to the rear of the axis of the low.

With this system, surface rainfall reports were more representative and gave a good picture of the rainfall pattern—better in some respects than that given by radar. This was because most of the rain fell from a broad, continuous area, with the intense cores confined to a small sector. Only when these cores were some distance from the radar set could their echoes be distinguished from the echo produced by the continuous rain area. But, of course, the rainfall reports separated the two régimes very clearly. The intense rain was confined to two areas—a very well-defined band about 10 to 15 miles broad and about 50 miles long accompanying the central parts of high C_1, and another, less well-defined area some 20 miles long, near the central parts of high C_2. The first area was already in the form of a well-organized row of intense cores when it first affected the south coast of England. Its western end entered extreme west Sussex at about 1000 GMT but, because of its alignment in a direction from north-west to south-east, places farther to the east experienced the intense rain at progressively later times; the eastern end crossed the coast near Hastings around 1100 GMT. The band moved in a remarkably uniform manner towards the north-east, crossing London soon after 1100 GMT, to lie along a line Cambridge to Ipswich at about 1200 GMT. It passed over north-east Norfolk at about 1300 GMT. At Horsham St. Faith, near Norwich, 11 millimetres of rain fell in 12 minutes. Indeed, throughout its life, intensities of one to three inches per hour were commonly experienced along the whole length of the band, but it was noticeable that the western end of the band became less intense, indicating that a progressive decay of the intense cores was slowly extending along the band from its western end. However, radar indicated that new cells were continually forming at its eastern end, so extending the band farther eastwards. The combined effect of these two processes—decay in the west and new growth in the east—was to make the band as a whole move in a direction across that taken by individual cells, and to their right.

The second area of intense rain moved into the extreme east of Sussex and into Kent at about 1200 GMT. No intensities greater than one inch per hour were reported, and the track of the area just skirted the coast of East Anglia. Radar showed that by 1300 GMT the intense cores were aligned with those of the first area in a direction almost north–south. Hail accompanied the intense rain in a few places, at Gatwick, Burlingham (near Norwich) and Gorleston, but these isolated reports probably do not indicate the true extent of hail. Hail also fell at Dover as high C_2 passed over.

Behind the bands of intense rain there were two extensive regions of continuous rain, each with remarkably uniform intensities of two to four millimetres per hour. Their extent corresponded very well with the extent of the highs C_1 and C_2, but their western edges were poorly defined because the rainfall intensity became progressively smaller, and therefore less easily recorded, farther away from the high centres. Other general features of the rain area associated with high C_1 were very similar to those of the rain area of high B: its westernmost part lagged behind the apparently faster-moving central part; it was about 50 miles broad; and its leading edge roughly corresponded with the position of the surge line (although in the west it lay about 20 miles to the rear of the surge line). In the eastern half of the area affected by system *C*, the two rain areas were largely continuous and gave a period of rain lasting about two hours. Not only were the leading edges of these rain areas clearly defined (especially the leading edges of the intense bands) but so also were the rear edges, although less sharply. These rear edges coincided most remarkably with the axes of the lows, the agreement being apparently to within a few miles.

Over the greater part of the system medium-level clouds were dominant, both stratiform and cumuliform, the typical combination being altostratus or nimbostratus with altocumulus floccus and castellanus beneath. Usually a complete cover was present, but in the rear of the wake lows, areas developed where the sky was nearly or wholly free of medium-level clouds. The exact relationship between these clear areas and the lows could not be found but they seemed to form some 50 to 100 miles behind the axes of the lows. One such area had spread into northern Hampshire and southern Wiltshire by about 1200 GMT, whilst the leading edges of another crossed the coasts of Hampshire and Sussex at about 1300 GMT, spreading north-north-east so that by 1500 GMT much of East Anglia and the south-east of England had only small amounts of medium-level clouds. Around the edges of these clear areas, cloud was mostly altocumulus stratiformis and lenticularis. The clear areas showed considerable extensions into the undisturbed airstream behind the meso-system.

Apart from medium-level cloud, system *C* was notable for its low-level clouds. Broadly, these were of two types:

(i) Cumulus mediocris and stratocumulus cumulogenitus, developing widely within the areas which were relatively free from medium-level clouds. They were produced by normal day-time heating of the ground. None of them developed into storms, thus giving further evidence to show that the storms which did occur were not formed by day-time heating.

(ii) Stratus fractus with a base of only a few hundred feet, developing widely within the rain-chilled air. Although mostly small in amount, at times it reached a full cover. This stratus was no doubt formed by turbulence developing within air near the ground which was already nearly saturated. The turbulence resulted from increased wind speeds caused by the intense pressure gradients of system *C*. Since winds strong enough to produce stratus existed behind low C_2, this cloud was observed over East Anglia after the rain had ceased. Little stratus accompanied the other systems, probably both because the turbulence was insufficient and because the surface air was not quite moist enough.

Thunder accompanying the intense rainstorms was severe, and damage by lightning was widespread over the area swept by the storms, from Sussex to Norfolk. Many flashes per minute were recorded in the most intense parts, especially around Norwich. Apart from the more usual effects of lightning such as broken masonry, fires, power failures and breakdowns in telephone systems, some more peculiar events were noted. As the storm belt crossed Great Yarmouth about 1230 GMT, lightning caused a clock in an hotel bar to stop and then some minutes later to start again—but backwards at twice its normal speed. A high-wire act at Oulton Broad Regatta was delayed for fear of lightning. Torrential rain caused local flooding in some towns, and in many places the storm belt was heralded by extreme darkness. At Diss, one member at a Rotary Club lunch had to strike a match to see if there was any butter on his plate. At Halesworth, the oldest inhabitants said of the gloom that they could not recall anything of a similar nature.

Some thunder and lightning were observed from the widespread rain area behind the severe storms, but all of it was slight.

Another effect of the storms, particularly those accompanying high C_1, was a sudden reduction in visibility as their cores passed overhead. Much of this reduction was no doubt caused by the raindrops themselves, together with an effect caused by a temporary increase in relative humidity. However, since the humidity was generally above 90 per cent even between storms, the latter effect was probably quite small. Throughout the region swept by the intense rain band, visibility was observed to fall rapidly from a value usually between three and six miles to one of 2,000 yards or less. Near the track of the high's centre, visibilities below 1,000 yards were common, whilst 550 yards was recorded at Wattisham. These changes occurred within a few minutes but the subsequent improvements were just as rapid.

Meso-system D.—The south-western boundary of system *C* was obscured by the overlapping remains of a smaller, inactive system *D*. It consisted of a narrow ridge occupying the periphery of its right-hand half, with a weak trough in its left half. The western and southern boundaries were difficult to find with accuracy because pressure changes were small. Also, its effect on the generally south to south-west winds was hardly noticeable, except on its right margin where outflow around the ridge was detectable at 1300 GMT to the west and north-west of London, and at 1400 GMT over Cambridgeshire. The only rain reported within its boundaries (to the north-west at 1300 and 1400 GMT) seemed to be a product of the larger system *C*. No radar echoes were reported, thus confirming the absence of rain. No thunder was heard. All these facts suggest that system *D* was weak and in an advanced state of decay.

Meso-system E.—Another weak system followed *D*. It first crossed the south coast near the Isle of Wight just before 1400 GMT. To a remarkable extent it resembled system *D*, consisting of a weak ridge in its right half, and a weak trough to the left. Like *D* its boundaries were difficult to determine exactly. Wind changes were slight and the little rain recorded seems to have been produced within the next system *F*.

Meso-system F.—By 1600 GMT another small system had moved into the extreme south-east of England. It consisted of a weak ridge followed by a trough, neither of them having separate centres in their isobars. The system moved north-north-east from Kent and Sussex to East Anglia with only a slight effect on the otherwise south-westerly winds; a temporary backing and a decrease in speed were noted between the axes of the ridge and trough. Rainfall was small in amount and slight in intensity, with a maximum of about five millimetres per hour. This centre of maximum intensity moved on a track to the east of London. Extending along a line through it and lying north-west to south-east was a belt of light rain which lay almost entirely within the trough. This contrasted with the three major systems *A*, *B* and *C* in which the rain was associated with high pressure, and perhaps indicated a state of decay, but not so advanced as found with *D* and *E*. The fact that no thunder was heard adds support to this suggestion.

Other meso-systems.—Study of detail on the barograms shown in Section 2.1 indicates that other very weak systems were present. However, their effects on the weather were so small as to make their definite identification almost impossible. System *Z* could be located on the meso-synoptic charts for 0600 and 0700 GMT but not for later hours.

3.3 *Causes of the pressure changes*

Probably since the time when barometers were invented it has been noticed that some thunderstorms are accompanied by sudden changes in atmospheric pressure. On a barogram such changes are clearly shown, and they contribute towards what Shaw called " the embroidery of the barogram ". Many and various have been the attempts to explain the changes, but the most important of them may be regarded as involving the following five physical processes:

(i) Vertical accelerations within the cloud, resulting from buoyancy.

(ii) Gravity waves, propagated along a horizontal boundary surface within the atmosphere.

(iii) Vertical transfer of horizontal momentum, when convection occurs in an atmosphere possessing vertical wind shear.

(iv) Frictional drag by falling precipitation, producing a downward acceleration of the atmosphere within the rain area.

(v) Cooling by falling precipitation, especially by its evaporation, which causes contraction and then convergence of air into the rain area.

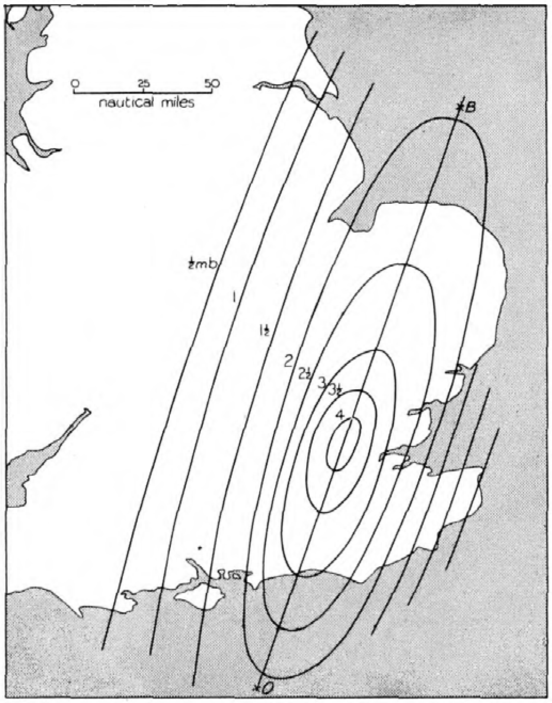

0 25 50
nautical miles
½mb
1
1½
2
2½
3
3½
4
B
O

FIGURE 26—ISOPLETHS OF PRESSURE RISE FOLLOWING SURGE LINE OF SYSTEM *B*

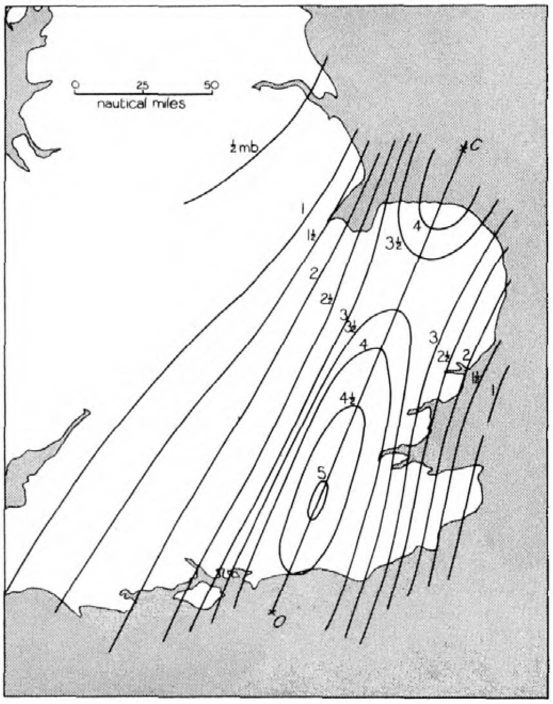
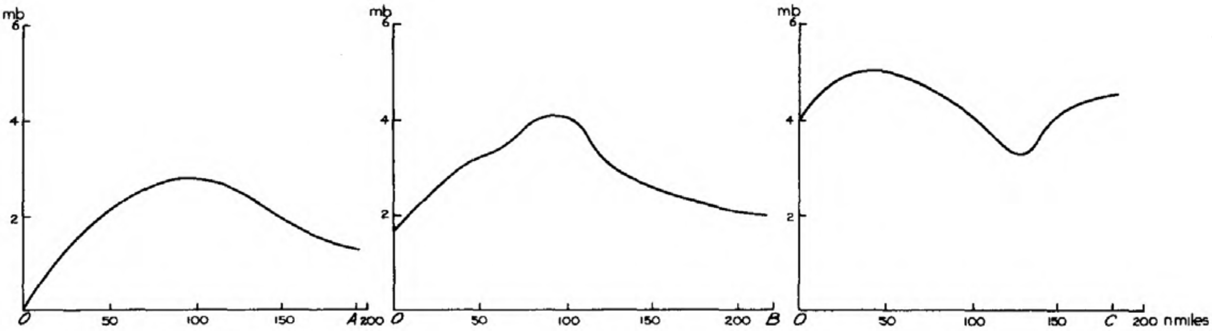
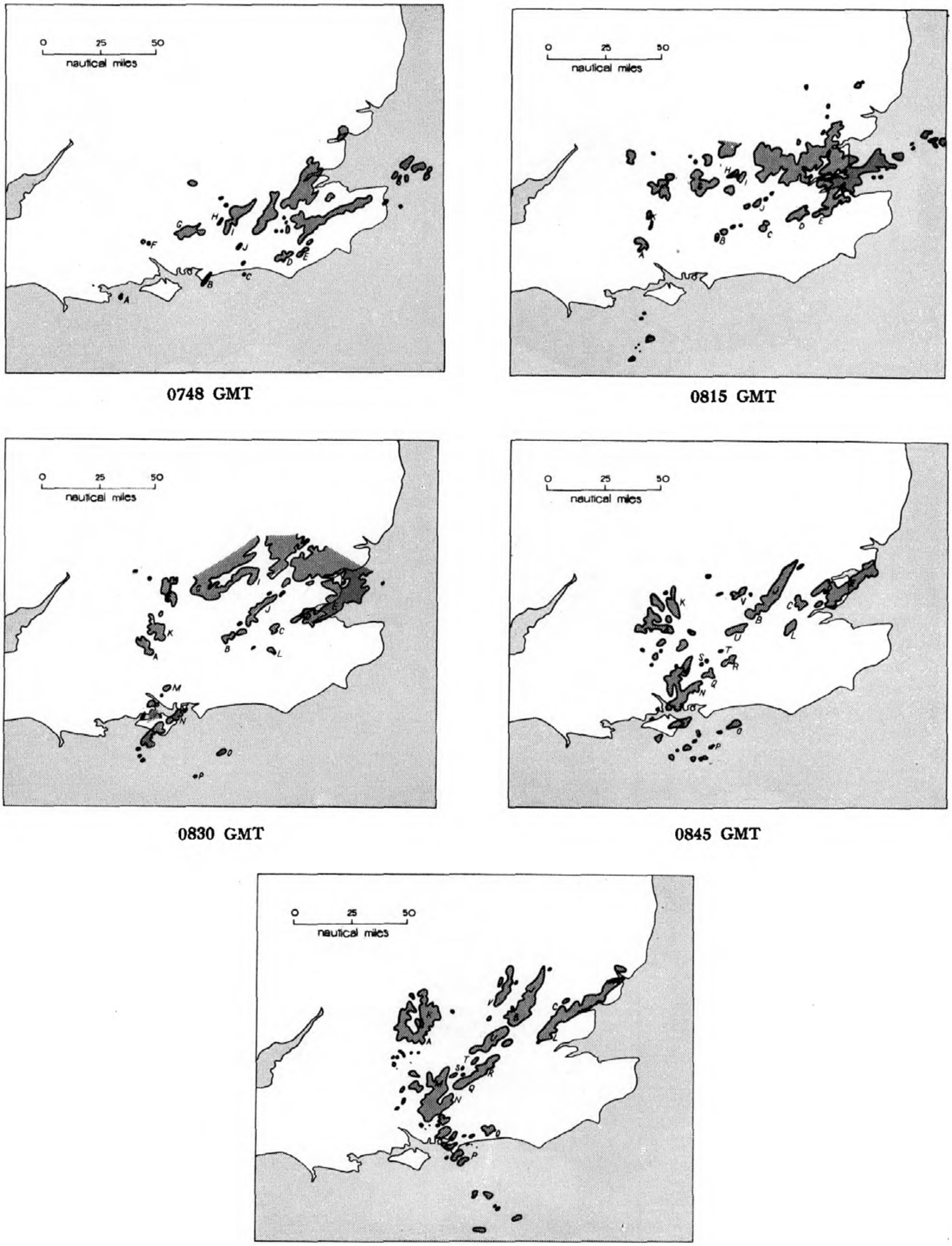

0 25 50
nautical miles
½mb
1
1½
2
2½
3½
4
3½
4
4½
5
3
2½
2
1½
1
C
O

FIGURE 27—ISOPLETHS OF PRESSURE RISE FOLLOWING SURGE LINE OF SYSTEM *C*



(*a*) System *A* (*b*) System *B* (*c*) System *C*

FIGURE 28—VARIATION OF MAGNITUDE OF PRESSURE RISE ALONG THE PATHS OF THE HIGHS OF SYSTEMS *A*, *B* AND *C*


0 25 50
nautical miles
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V

0748 GMT

0815 GMT

0830 GMT

0845 GMT

0900 GMT

FIGURE 29—EVOLUTION OF ECHOES FROM CELLS WITHIN MESO-SYSTEM *A*

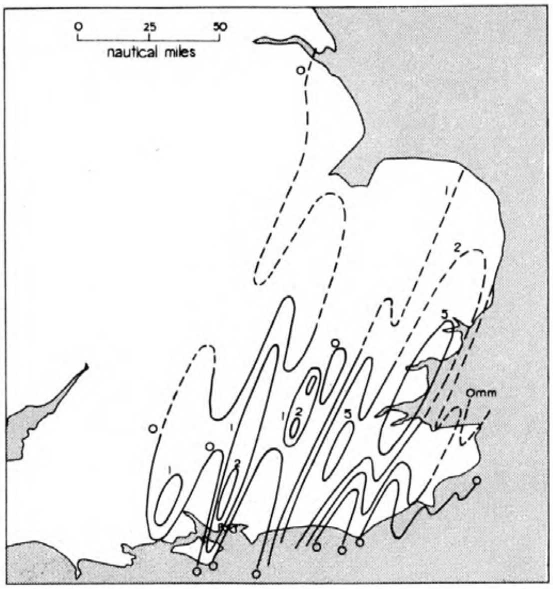
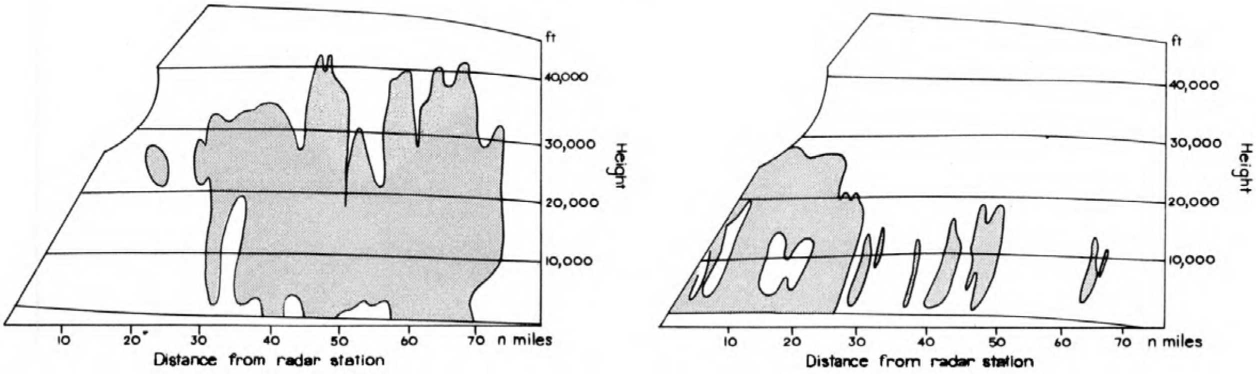


FIGURE 30—TOTAL RAINFALL FROM SYSTEM *A*
Dashed lines are very approximate because of lack of data.



(*a*) Time: 0754 GMT. Bearing: 141° true.

(*b*) Time: 0857 GMT. Bearing: 009° true.

FIGURE 31—RANGE HEIGHT INDICATOR RADAR CROSS-SECTIONS THROUGH MESO-SYSTEM *A*

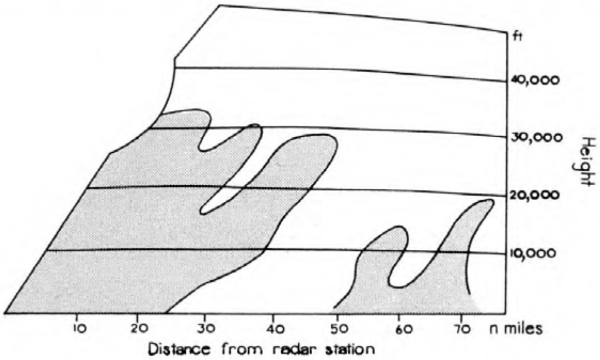


FIGURE 32—RANGE HEIGHT INDICATOR RADAR CROSS-SECTION THROUGH MESO-SYSTEM *B*
Time: 1022 GMT. Bearing: 014° true.

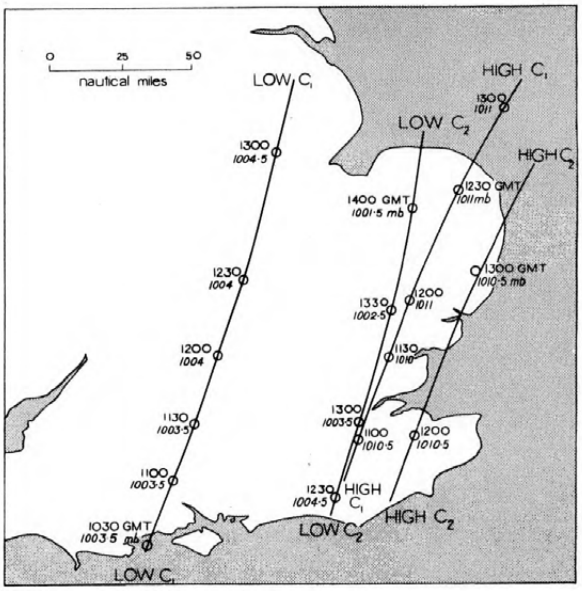

0 25 50
nautical miles
LOW C₁
HIGH C₁
LOW C₂
HIGH C₂
1300 1004·5
1230 1004
1200 1004
1130 1003·5
1100 1003·5
1030 GMT 1003·5 mb
1300 1011
1230 GMT 1011mb
1200 1011
1130 1010
1100 1010·5
1400 GMT 1001·5 mb
1330 1002·5
1300 1003·5
1230 1004·5
1300 GMT 1010·5 mb
1200 1010·5
HIGH C₁
LOW C₂
HIGH C₂
LOW C₁

FIGURE 33—TRACKS OF THE FOUR CENTRES IN MESO-SYSTEM *C* Pressures at the centres are shown in italics and are given to the nearest half millibar every half-hour.

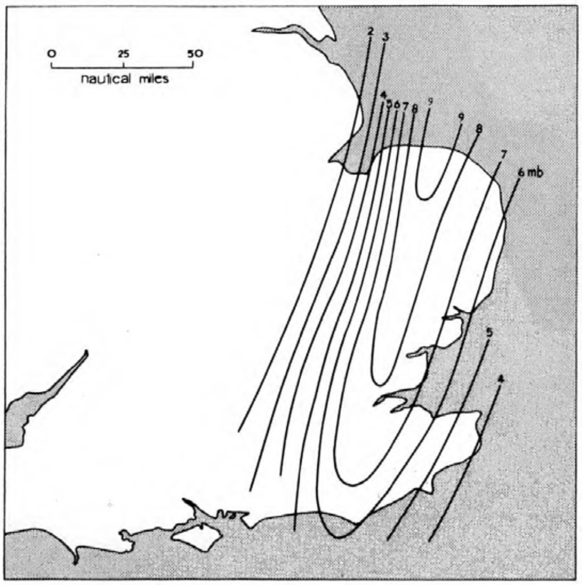

0 25 50
nautical miles
2
3
4
5
6
7
8
9
9
8
7
6 mb
5
4

FIGURE 34—ISOPLETHS OF PRESSURE CHANGE BETWEEN HIGH C_1 AND LOW C_2

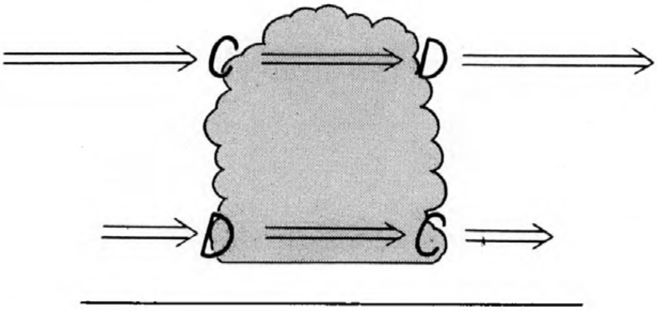


FIGURE 35—PATTERN OF CONVERGENCE (*C*) AND DIVERGENCE (*D*) RESULTING FROM CONVECTION EMBEDDED IN AN ATMOSPHERE POSSESSING VERTICAL SHEAR Wind speeds are proportional to lengths of arrows.

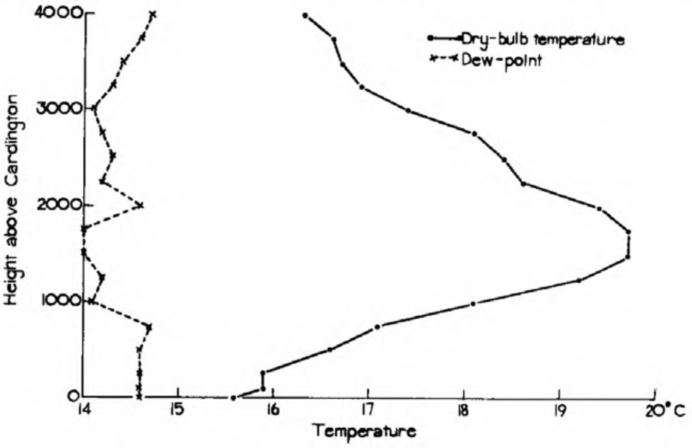


FIGURE 36—SOUNDING OF TEMPERATURE AND DEW-POINT (BALTHUM) ABOVE CARDINGTON AT 0060 GMT 28 AUGUST 1958

The presence of vertical currents inside thunderstorms is well known. It follows, then, that vertical accelerations must occur so that these currents may be initiated. When vertical accelerations are present the hydrostatic equation can no longer be assumed to be applicable to the atmosphere because the vertical forces on a parcel of air—resulting from gravitational attraction and the vertical pressure gradient—are no longer balanced and the parcel is buoyant. Quantitative assessments of the effects of vertical accelerations on surface pressure were made by Levine[1]*, Buell[2] and Schaffer[3], but Suckstorff[4] had already suggested that pressure changes during thunderstorms might have a dynamical origin. Criticisms of these quantitative treatments, especially by Mull and Rao[5] and by Brooks[6], have shown that the arguments were invalid on several grounds, including neglect of the upward decelerations aloft which must accompany upward accelerations at lower levels, and also neglect of temperature and density differences between cloud and its environment. Schaffer[7] has pointed out that we cannot assume a steady state to be normal inside a thunderstorm, and as a consequence some of the pressure changes might well be quite local, resulting from rapid and short-lived developments within the cloud.

When the cloudy air is moving vertically relative to its environment, a third force comes into play—frictional drag between the two. Observations upon the rate of growth of cumulus tops by Malkus and Scorer[8] have shown that this force is easily capable of balancing buoyancy so that, in fact, the cloudy air does not accelerate but maintains an approximately constant vertical speed. It seems that the net effect of buoyancy is to produce little or no effect on surface pressure.

Gravity waves undoubtedly exist in the atmosphere, and Tepper[9,10] has proposed that the pressure surge line (or " pressure jump line " as he called it) is an example of such a wave, and also that the wave presents a steep front to account for the very sudden pressure change which follows the surge line. The wave travels along a horizontal boundary surface in a two-layer atmosphere, such as occurs when an inversion separates two layers each having only small stability. If the upper layer is potentially unstable, the passing of the gravity wave may well lift it sufficiently to trigger off convection. Tepper based his suggestion on a detailed micro-synoptic analysis of part of a pre-cold frontal squall line, using micro-synoptic charts at one-minute intervals. The squall line he studied seems to be quite typical with its intense pressure gradient, wind shift, temperature drop and heavy rainfall. However, his contention that because pressure is observed to be the first of all the meteorological elements to change that it must therefore be the cause of changes in the others is hardly possible. This is particularly so when rainfall is considered. The short time interval, five or ten minutes, between the surge and maximum pressure is far from sufficient to allow the growth of the intense rainfall observed. More direct evidence for the incorrectness of Tepper's idea arises from two consequences of it, namely, that the gravity wave should be in existence before the storms, and that comparable down-surges of pressure should coexist with the up-surges. This study shows, as do others in the United States of America, that the storms appear first and that they subsequently may develop pressure surge lines. Also, down-surges in the form of wake depressions appear only in the later stages of meso-systems when the thunderstorm highs are well established. Although gravity waves may initiate storms by their ability to lift potentially unstable air so that convection is released, it seems that the pressure changes are caused, at least largely so, by other means. (See Tepper[11], however, for an example of cloud dispersal by a gravity wave.)

Mull and Rao[5] have pointed out that when deep convection develops in an airstream having vertical wind shear, it must interfere with the wind flow. If a storm develops in an airstream whose wind speed increases with height but whose direction is constant, and if the speed of the storm is intermediate between the wind speeds of the environment at the levels of the base and top of the storm, then the base of the storm will be moving faster than its environment. This produces convergence at the leading edge of the storm at low levels, and divergence in the rear.

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* The index numbers refer to the bibliography on p. 38.

Conversely, aloft the storm moves slower than its environment with resulting divergence on the leading edge and convergence in the rear. This situation is shown in Figure 35. Newton and Newton[12] have calculated the magnitudes of pressure changes which result from this pattern of convergence and divergence. They are in the order of one millibar, and may well contribute significantly to the observed changes.

It is unlikely that the horizontal speed of the cloud will be the same at all levels as shown in Figure 35. Indeed, observation of the development of a single-celled cumulonimbus cloud shows that the top streams away downwind, forming a characteristic " anvil ". With such a comparatively small cloud, the difference between cloud speed and environment speed at any given level is small, that is, the cloud largely takes up the speed of its environment, level for level. However, when the storm is massive, consisting of numerous adjacent cells, it acts as a bigger obstacle to the wind flow and it causes the distribution of convergence and divergence to approach the condition shown in Figure 35. As a further aid, mixing of in-cloud air by the powerful vertical currents present cause the in-cloud shear to be smaller than the shear in the environment. The result is that the larger is the storm system, the larger are the pressure changes. Douglas[13] also has pointed out that sudden pressure falls seem to be associated with the coexistence of medium-level instability with vertical shear. This combination does not, however, seem to be essential to the production of pressure falls. In a study of some almost stationary meso-systems by Fujita[14], meso-lows appeared later in their life-cycles.

The very close association between rainfall and pressure rises is repeatedly shown by the meso-synoptic charts of Section 3, so it is natural to look for a physical connexion between them. Shaw and Dines[15] suggested that the pressure rises might be caused by precipitation but they did not specify the relationship. Suckstorff[16] linked them with the downdraught which he had observed in mature thunderstorms. Byers and Braham[17], as part of the results of the Thunderstorm Project in the United States of America, showed that the downdraught was caused, at least in part, by the frictional drag of falling precipitation. Hence it is reasonable to expect that the downward acceleration imparted by the frictional drag would produce a pressure rise at the ground as the downdraught is forced to spread sideways (Brooks[18]). The magnitude of the pressure rise will increase with the speed which the downdraught has reached before it spreads out below the cloud. This speed will be controlled by a balance between the forces producing the downdraught—a balance between frictional drag caused by the precipitation which is pulling the air down, frictional drag between the downdraught air and its environment, and any buoyancy the downdraught may have as a result of its density being different from the density of its surroundings. All three are difficult to estimate, but the resulting rise in pressure is likely to be small although increasing with the rate of rainfall. In any case the rise would be confined to a small area immediately beneath the downdraught. Fujita[19] has suggested that it may contribute to the sharp " pressure nose " which appears to be associated always with the cores of intense rainfall.

There is another mechanism which relates the pressure rises with precipitation. Brooks[18] has pointed out that pressure rises persist after precipitation has ceased or at least considerably decreased in intensity, and this is well shown in the meso-synoptic charts of this study. It follows that pressure rises can be the result of effects other than dynamic. Mull and Rao[5] and Bleeker and Andre[20] suggested that cooling of the air through which precipitation is falling, partly by conduction but more especially by evaporation into the unsaturated air below cloud base, would result in contraction and the resulting convergence of air from the surroundings would give a pressure rise at the ground. Removal of latent heat from the air to cause the melting of snow or hail falling through it would assist the cooling (Fujita[19]).

In a now classical case of meso-synoptic analysis, Fujita[21] ascribed the pressure rise in a thunderstorm high to the relatively dense, cold air of the downdraughts spreading out from the storm centres. Some later calculations by Fujita[19] have substantiated this idea by showing that the total excess mass of cold air in the thunderstorm high is proportional to the amount of rain which has fallen.

If the pressure rises are caused by evaporation of rain into the air below cloud base, it is to be expected that the greatest rises will occur when the cloud base is highest. Many case studies of thunderstorms indicate that large pressure changes do indeed accompany storms in hot, dry weather. A nine-millibar rise was reported in an Australian storm by Storer[22]. Bhalotra[23, 24], in a study of squalls at Delhi, has found that May is the most favourable month for large changes and that during this month the lapse rate is approximately equal to the dry adiabatic value from the ground up to three or four kilometres, with the cloud base at this level. By contrast, at Bombay, George[25] has found that the pressure rises accompanying squalls are usually small during the south-west monsoon. This is to be expected from the moistness of the air and predominantly low cloud bases. With pre-monsoon and post-monsoon thunderstorms at Bombay, pressure changes are larger because such storms develop in drier air. At Peshawar, Ramaswamy and Majumdar[26] have found that squalls have similar properties to those at Delhi. From a study of thunderstorms with cloud bases as high as 10,000 to 12,000 feet, Krumm[27] has found evidence to confirm an idea put forward earlier by Braham[28] that the downdraughts themselves are the result of evaporational cooling below cloud base.

It will now be shown that the magnitude of the pressure rise is proportional to the square of the height of the cloud base, as long as certain reasonable assumptions are made about the way by which the air is cooled. We shall assume that the cooling is confined to the air below cloud base. This is reasonable since evaporation, not conduction of heat to cold precipitation, is the main cause of cooling, and evaporation can occur only in the unsaturated air below cloud. There is some observational evidence to support this assumption. In two case studies, Fujita[19, 29] showed that the thunderstorm high and the cold air producing it were present only below about 5,000 feet.

Consider the layer of air below a cloud whose base is at a height h. In the initial state, before cooling by evaporation, let the linear lapse rate between the ground and cloud base be γ and the temperature and pressure at the ground and cloud base respectively be T_g and P_g, T_b and P_b. Combining the hydrostatic relation $dP = -\rho g dz$, where ρ is the density of the air and z is height measured upwards from the ground, with the general gas law $P = \rho RT$, we obtain:

$$\frac{dP}{P} = -\frac{g}{RT}dz = \frac{g}{\gamma R}\frac{dT}{T}.$$

Integrating from the ground to cloud base:

$$\ln\frac{P_g}{P_b} = \frac{g}{\gamma R}\ln\frac{T_g}{T_b} = \frac{g}{\gamma R}\ln\left(1 + \frac{\gamma h}{T_b}\right).$$

In the final state, after cooling by evaporation, let the lapse rate between the ground and cloud base be γ' and the temperature and pressure at the ground be T_g' and P_g'. At cloud base, temperature and pressure will be unchanged. Integrating as before, we obtain:

$$\ln\frac{P_g'}{P_b} = \frac{g}{\gamma' R}\ln\left(1 + \frac{\gamma' h}{T_b}\right).$$

Subtracting the preceding equation from this,

$$\ln\frac{P_g'}{P_g} = \frac{g}{\gamma' R}\ln\left(1 + \frac{\gamma' h}{T_b}\right) - \frac{g}{\gamma R}\ln\left(1 + \frac{\gamma h}{T_b}\right).$$

Writing $P_g' = P_g + \Delta P$, where ΔP is the pressure rise resulting from evaporation, and expanding the logarithms, retaining first order terms on the left-hand side and second order terms on the right, we obtain:

$$\frac{\Delta P}{P_g} = \frac{gh^2}{2RT_b^2}(\gamma - \gamma'),$$

that is,
$$\Delta P = Kh^2,$$
where
$$K = \frac{gP_g\,(\gamma - \gamma')}{2RT_b^2}.$$

The value of γ is likely to be equal to the dry adiabatic lapse rate, 10° C per kilometre. The value of γ' is likely to be equal to the saturated adiabatic lapse rate, say 6° C per kilometre, because the wet-bulb potential temperature is likely to be constant with height. With these values for the lapse rates and the following approximate values for the other quantities:

$$g = 980 \text{ cm sec}^{-2},$$
$$P_g = 10^6 \text{ dyne cm}^{-2},$$
$$R = 2{\cdot}6 \times 10^6 \text{ erg °A}^{-1} \text{ gm}^{-1},$$
$$T_b = 300° \text{ A},$$

then $K = 0{\cdot}8 \times 10^{-7}$ dyne cm^{-4}. If ΔP is expressed in millibars, and h in kilometres, then:

$$\Delta P \approx 0{\cdot}8h^2. \qquad (1)$$

Over Britain, cloud bases in heavy storms are seldom above two kilometres so that the maximum pressure change caused by evaporation is unlikely to exceed about three millibars. This conforms with experience. In this study, the bases were at about three kilometres, thus permitting a maximum pressure rise of about seven millibars which is comparable with the observed maximum changes. Rises of five to ten millibars sometimes accompanying severe storms in dry climates are just what one would expect from this result.

Equation (1) indicates the *maximum* pressure rise. The *observed* rise in a storm will be less than this for several reasons.

(i) The air below cloud base may not become completely saturated by the falling rain, that is, γ' may not be equal to the saturated adiabatic lapse rate. This will be so during the early stages of a storm, but the longer the rain continues the greater will the pressure rise become. Figures 25 to 28 show the isopleths of pressure rise for each of the three major thunderstorm highs and the variation with time of the rise observed along the track of the centre of each high. With the first high, both centres seem to have started near the south coast of England and then to have developed as they moved northwards. The westernmost was the more short-lived, reaching a maximum rise of 1·5 millibars in about 45 minutes after initiation, whereas the easternmost centre was more vigorous and persistent, reaching a maximum rise of near 3 millibars after about 90 minutes.

(ii) The layer cooled by evaporation may not extend the whole distance from ground to cloud base because the cold dense air formed inside the rain area will spread outwards from the storm centre in the form of a shallow layer near the ground. The depth of this layer is likely to decrease as the cold air spreads out from the storm centre, so giving a smaller pressure rise. This spreading by subsidence, resulting from the denseness of the air within the thunderstorm high, will also continue after the rain has ceased. When this happens, the size of the pressure rise decreases over the whole area of the high. In both Figures 25 and 26 each centre shows a pressure rise of decreasing magnitude at the downwind end of its track; but in Figure 27 the pressure rise increases again over Norfolk after first reaching a maximum over Essex, probably the result of intensifying convection as the storms moved across East Anglia.

(iii) Even when evaporational cooling takes place below the cloud, a pressure rise does not follow immediately. The first effect of the cooling is to make the air below the cloud contract, with the result that the isobaric surfaces through the rain area dip downwards slightly. This process is the reverse of that occurring with a sea-breeze where the isobaric surfaces are first lifted as a result of the air near the ground being heated over land. The resulting pressure gradients aloft within the rain area produce an inflow and convergence there, so that surface pressure rises. It is clear, however, that a detectable rise will not be observed until some finite time after the rain starts. This time is probably in the order of 15 to 30 minutes. As a consequence of this, the early stages of a storm will be accompanied by little or no pressure change. Also, the pressure rise at any given time during the life of the storm will lag behind the value it would be if convergence were instantaneous, so that the greatest rise may be found after the heaviest rain has ceased.

(iv) If the original lapse rate below the cloud is less than the dry adiabatic value, the pressure rise will be less than that given by equation (1) above. In this case study, an inversion was present near the surface as can be seen in Figure 36 where the BALTHUM ascent for Cardington at 0600 GMT is shown. The inversion was the product of both radiational cooling during the previous night and advection of warm air above the film of cold air near the ground. In effect it reduced the depth of the layer cooled by evaporation.

So far, we have been considering pressure *rises*; the origins of pressure falls are less well understood. Clearly defined meso-lows almost always seem to be associated with pronounced thunderstorm highs. Fujita[21] found that they developed some hours after the appearance of the accompanying high, and that their positions relative to the high centre depended upon the relative motion of the high and the winds in its environment at low levels. If the high and its storms move faster than the low-level winds, then the meso-low appears in the wake of the high; it is then known as a wake low. This is the most usual situation, and was the one present in this case study. Fujita suggested that the pressure fall was the result of the mass of rain-cooled air being forced through its slower-moving environment in the same way that the pressure falls in the lee of an obstacle on the ground when the wind blows past it. The fact that the pressure fall is greatest when the adjacent high is most intense supports this suggestion. Brunk[30] has put forward the idea that the tops of towering convective clouds may set up gravity waves on the tropopause which would then produce pressure fluctuations at the ground.

3.4 *Origin of the storms*

Several facts indicate that the storms were not set off by surface heating over Britain: firstly, some of them were already well developed when they crossed the southern coast of England; secondly, of those which did form over land, some appeared only a few hours after sunrise; thirdly, eye observations showed that the storms started at medium levels; and fourthly, over much of the area affected by the storms, stable conditions, or even an inversion, were persistent near the ground.

Figure 37 shows the results of radio-sonde ascents made at Hemsby at 2300 GMT on 27 August and at 1100 GMT on 28 August, that is well before and during the storms, respectively. Both ascents show potential instability. Thus at 2300 GMT the wet-bulb potential temperature decreases upwards from 18° C near the ground (except for a thin surface layer) to a minimum of 16° C around 600 millibars, and then it increases to reach 18° C again by about 350 millibars. It follows from this that potential instability existed from near the ground up to about 25,000 feet. Now potential instability such as this is a contributory cause to violent convection, but although it is necessary it is not sufficient. The convection must be released by the bodily lifting of the atmosphere until such a depth has become saturated that the accompanying change in lapse rate has produced conditional instability. When this has been reached, violent convection results. The first convective cloud is likely to appear in the layer of highest relative humidity. From Figure 37 this is seen to be between about 800 and 700 millibars at 2300 GMT, for which layer the lifting condensation level is between about 750 and 650 millibars. Hence, the first cloud would be at medium levels with bases between 8,000 and 12,000 feet, agreeing very well with reported values.

As progressively deeper layers become saturated by lifting so the base would descend somewhat but, more particularly, the tops would build to higher levels. However, Figure 37 suggests that about 25,000 feet would be the maximum cloud top, a value considerably less than those reported. This difference can probably be explained in the following way. Considering the 1100 GMT ascent, we see that the wet-bulb potential temperature decreases upwards from about 20° C near the ground to a minimum of 16° C around 650 millibars, and then it increases to reach 20° C again at about 270 millibars. At 1100 GMT potential instability existed from near the ground up to about 32,000 feet. Bodily lifting, if it proceeded far enough, could allow convection to reach up to this level. If air with a wet-bulb potential temperature of 20° C were injected *at low levels* into an atmosphere whose properties were otherwise as shown by the 2300 GMT ascent, then spontaneous convection would occur (after the initial bodily lifting) up to near 200 millibars or, say, 38,000 feet, which agrees quite well with reported values of the highest tops. However, these heights could have been reached only if the in-cloud air remained undiluted with air entrained from its surroundings at medium levels. Inside massive storms, this could occur.

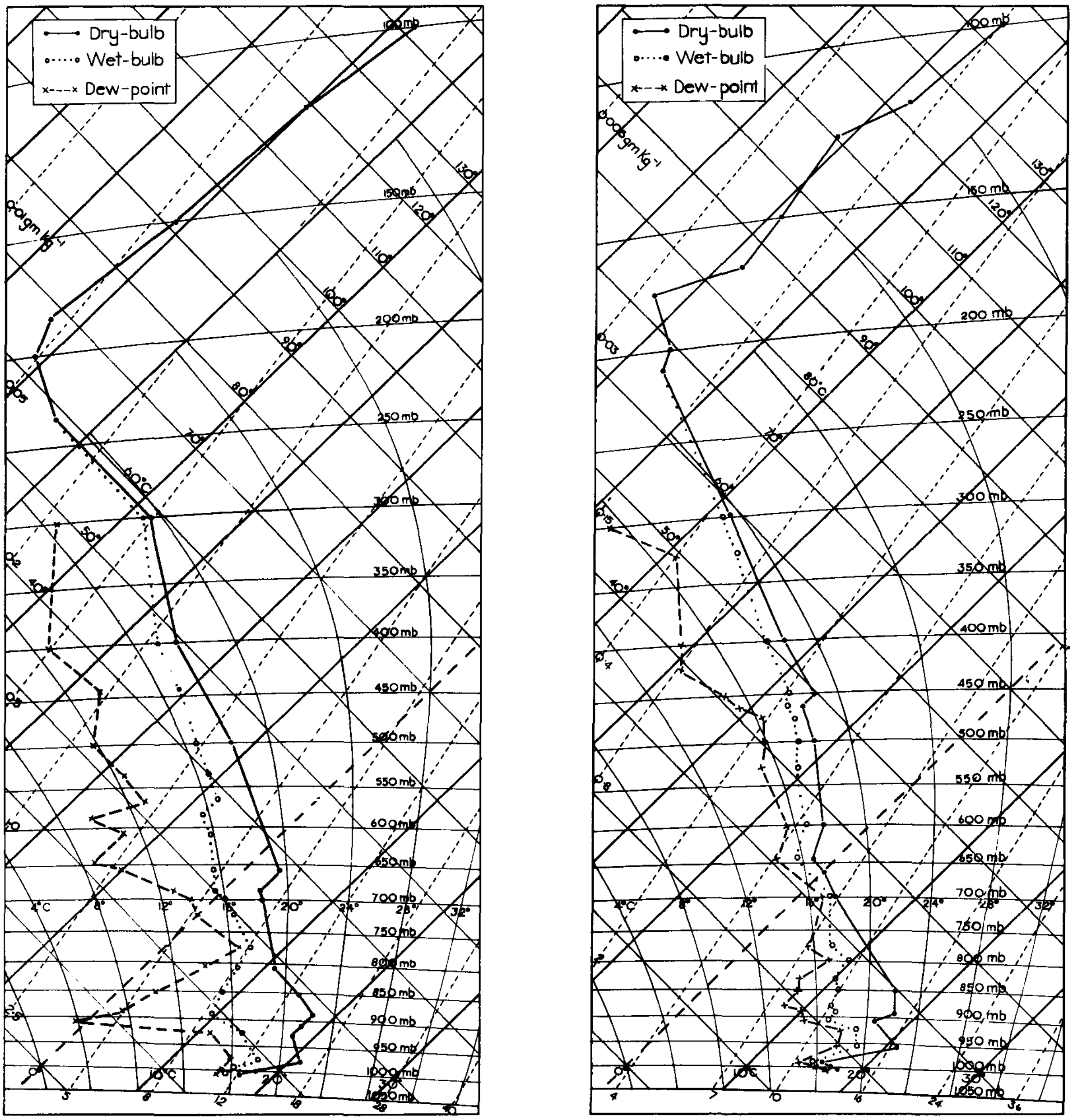
The injection of air at low levels with a wet-bulb potential temperature near 20° C could have been brought about by advection. To test this, charts of the 850- and 500-millibar surfaces were drawn for midnight and midday, and on them isopleths of wet-bulb potential temperature were drawn. These charts are shown in Figures 38 and 39. At midnight (Figure 38) the 850-millibar chart shows a depression in the eastern part of the North Atlantic and a ridge over Europe with its axis from Algeria to Scandinavia. Between them a south-south-westerly stream covers western Europe, and in it a tongue of warm moist air (shown by the 20° C isopleth) is extending from eastern Spain into south-western France. The 500-millibar chart is very similar in appearance, but the axis of the ridge is a little to the west of its position at 850 millibars, and the wet-bulb potential temperature nowhere exceeds about 18° C. By the following midday (Figure 39) the south-south-westerly winds have advected the warm, moist tongue at 850 millibars across much of France, into Belgium and the south-eastern corner of England, whilst at 500 millibars few changes have taken place except the advection of warm, moist air across Spain. Because of this differential advection, a wide area of potential instability developed during the morning over south-eastern England, Belgium and France. A rough measure of the extent of this instability is given by subtracting the value of the wet-bulb potential temperature at 850 millibars from the value at 500 millibars. Isopleths of this temperature difference are shown in Figure 40 for both midnight and midday. Negative values indicate potential instability. On the midday chart (Figure 40(*b*)) the area over which thunderstorms were occurring at that time is shown by heavy shading. Its western edge is neatly bounded by the 0° C isopleth, but its eastern edge does not include the zone of greatest potential instability over the extreme north of France. In fact, the storms are confined to the western side of the tongue of potential instability extending from the western Mediterranean to the southern North Sea. This is to be expected since it is this part of the tongue which is affected most by the bodily lifting necessary for releasing the instability.

Another use of the isopleths of wet-bulb potential temperature shown in Figures 38 and 39 is in distinguishing the air masses. Surface temperatures were found to be unsuitable for this purpose because of effects of the previous night's radiational cooling, and also of variable insolation in areas of different cloudiness. Close isopleths indicate fronts, and widely spaced isopleths indicate fairly uniform air masses. It can be seen that the warm sector at 850 millibars is much narrower than it is at 500 millibars. Little change in the configuration of the fronts took place between midnight and midday. The cold front has a much steeper slope than the warm front, and there is a suggestion from the slight bend in the 850-millibar contours over the Bay of Biscay at midnight that there is a shallow wave there. By midday this wave seems to have moved up over the Midlands. Behind the cold front, moist polar air is moving northwards over western Britain, whereas ahead of the warm front, dry subsided polar air is moving north over central Europe.

It can be seen that the thunderstorms developed between the cold front and the axis of the warm, moist tongue at 850 millibars. Fawbush, Miller and Starrett[31] have found that the presence of a relatively narrow tongue of warm, moist air at low levels is essential to the formation of severe storms. They also showed that this tongue was produced by a belt of strong winds, or jet, at low levels. In this study a jet core lay just to the east of the cold front with its axis at a height of about three kilometres. Figure 41 shows a cross-section through this jet, along the line from Valentia in Ireland to Payerne in Switzerland. The isopleths show values of the wind component perpendicular to the line of section, that is, blowing from 200°, which is approximately parallel to the general flow in the troposphere. Two jets are evident. One, centred at about 37,000 feet some 50 miles east of Aldergrove, probably reaches a maximum speed of near 130 knots. The other jet is less well marked and passes near Crawley at only 11,000 feet; the maximum speed reaches about 80 knots which is remarkably large for such a low level. Over south-east England winds are fairly uniform at about 60 knots between 10,000 and 35,000 feet, but there is marked vertical shear below 10,000 feet. Both Macdonald[32] and Means[33], in studies of conditions leading to severe storms, have pointed out that warm advection at low levels is greatest along a narrow band, whilst Carr[34], Chapman and Carr[35], Nash and Chamberlain[36] and Lee[37], in particular case studies, have shown that advection of warm, moist air at low levels within the warm sector of a depression has led to the formation of heavy rainstorms and tornadoes. The importance of differential advection has been pointed out by Miller[38] and by Whitney and Miller[39], and they showed that it favoured convection on three counts: by decreasing the amount of work needed to lift the air; by decreasing the height through which the air must be lifted before it will rise spontaneously; and by increasing the amount of energy available to the convective system.

For many years it has been known that typical pre-tornado conditions in the United States of America show moist air at low levels surmounted by an inversion with warm, dry air above. Varney[40] and Humphreys[41] were among the first to point out this structure, but it was not until later (for example, Lloyd[42]) that the presence of potential instability was realized. An analysis of tornado proximity soundings by Beebe[43] has shown that the low-level inversion is absent close to severe storms and that the ascent then much more closely resembles the mean thunderstorm soundings found by Byers and Braham[17]. This conversion is caused by vertical stretching of the atmosphere resulting from either convergence at low levels or divergence aloft, or both. In a case study of heavy warm-sector rains, Oliver and Shaw[44] have shown that low-level convergence was an important factor in their formation; Breiland[45] has also emphasized its importance in the release of instability. Sangster[46] has explained the observed maximum frequency of thunderstorms and heavy rains over the central United States of America in the early hours of the morning as being the result of a diurnal variation of low-level convergence. This variation is caused by a pulsation of the southerly winds in which the storms form, the pulsation in its turn probably being caused by the diurnal variation of vertical transfer of momentum near the ground as the night-time surface inversion develops. When the night-time inversion is present, turbulent mixing above it is much less than at the same levels during the day so that the winds there are strongest at night (Blackadar[47]). Boucher[48] gives evidence to show that over New England, convergence, caused there by the sea-breeze, increases severe storm frequency at places just inland from the coast.

Whereas some investigators have stressed the need for low-level convergence in releasing convective instability, others have favoured divergence aloft. The effective level of divergence has been variously taken as either 500, 300 or 200 millibars. Case studies of severe storms by Nash and Chamberlain[36], Lee[37], Miller[49], Sugg and Foster[50] and Hanks and Neubrand[51] all indicated divergence aloft as shown by the patterns of wind flow. Commonly this takes the form of a region with decreasing cyclonic curvature of the contours downwind from the axis of an upper trough. The presence of a jet stream aloft through this region seems almost essential. Synoptic studies of squalls over the north central United States of America by Porter, Means, Hovde and Chappell[52], and of squalls over Delhi by Bhalotra[24], have also shown the importance of slowly moving troughs aloft with the storms forming somewhat downwind from their axes.



(*a*) 2300 GMT, 27 August

(*b*) 1100 GMT, 28 August

FIGURE 37—TEPHIGRAMS OF SOUNDINGS MADE AT HEMSBY, 27 AND 28 AUGUST 1958

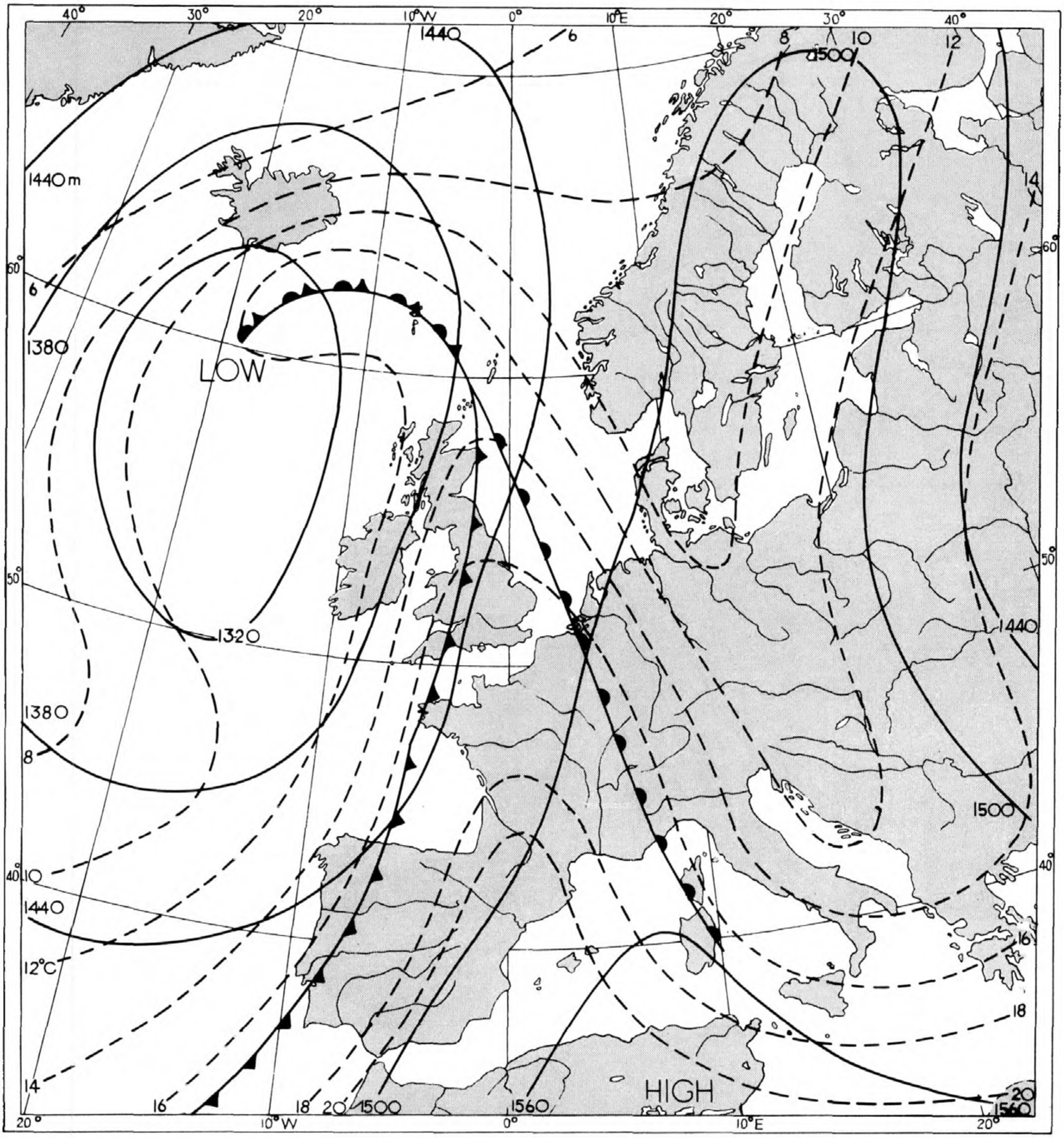

40°
30°
20°
10°W
0°
10°E
20°
30°
40°
1440
6
8
1500
10
12
1440 m
60°
6
1380
LOW
1320
50°
1380
8
40°
10
1440
12°C
14
16
18
20
1500
1560
HIGH
20°
10°W
0°
10°E
20°
14
60
50
1440
1500
40
16
18
20
1560

FIGURE 38(*a*)—CONTOURS, ISOPLETHS OF WET-BULB POTENTIAL TEMPERATURE AND FRONTS, AT 850 MB, 0001 GMT, 28 AUGUST 1958

Contours are shown by continuous lines and isopleths of wet-bulb potential temperature by dashed lines.

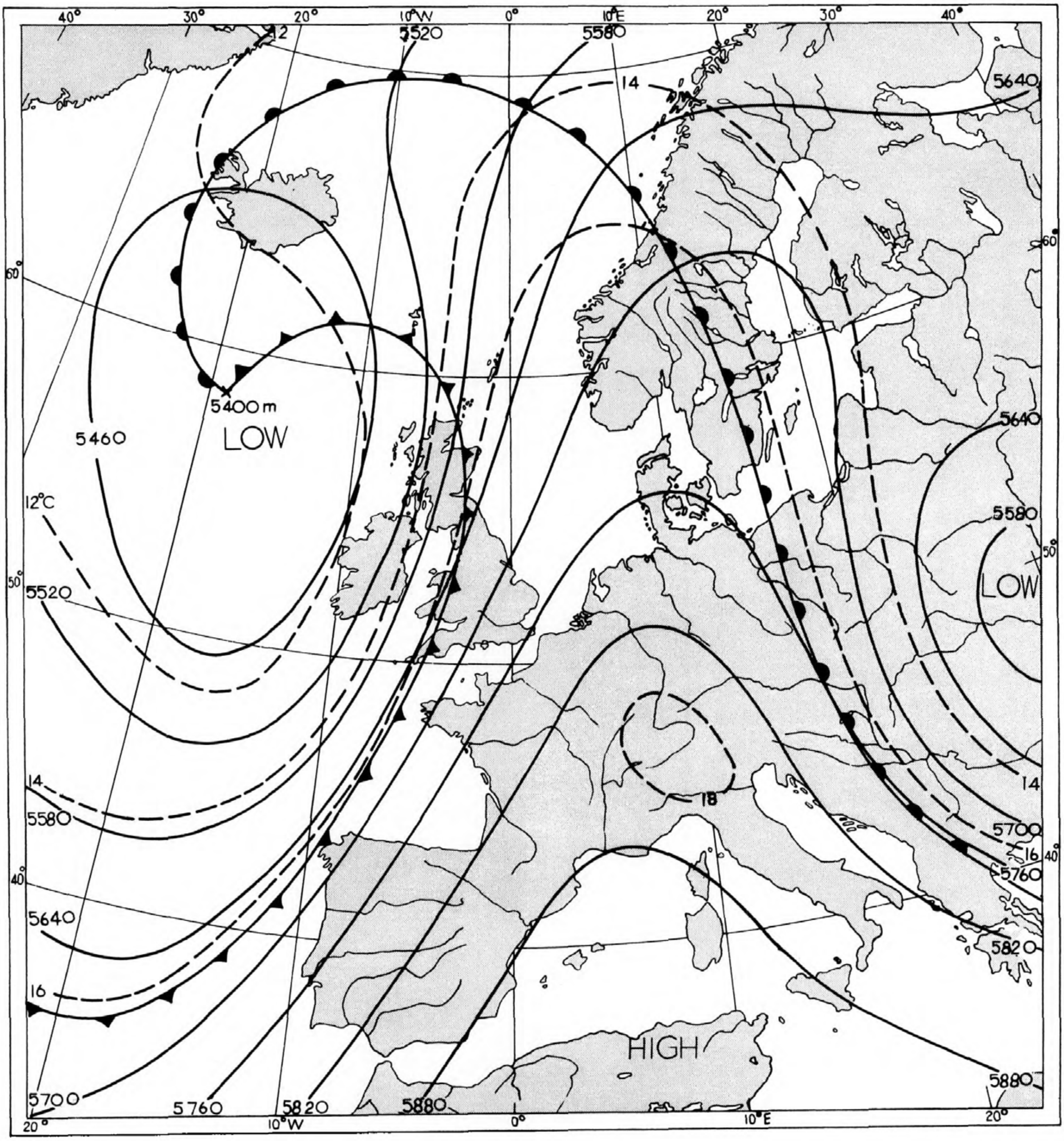

40°
30°
20°
10°W
0°
10°E
20°
30°
40°
12
5520
5580
14
5640
60°
60°
5400 m
LOW
5460
12°C
5640
5580
50°
50°
5520
LOW
18
14
14
5580
5700
16
5760
40°
40°
5640
5820
16
HIGH
5880
5700
5760
5820
20°
10°W
0°
10°E
20°

FIGURE 38(*b*)—CONTOURS, ISOPLETHS OF WET-BULB POTENTIAL TEMPERATURE AND FRONTS, AT 500 MB, 0001 GMT, 28 AUGUST 1958

Contours are shown by continuous lines and isopleths of wet-bulb potential temperature by dashed lines.

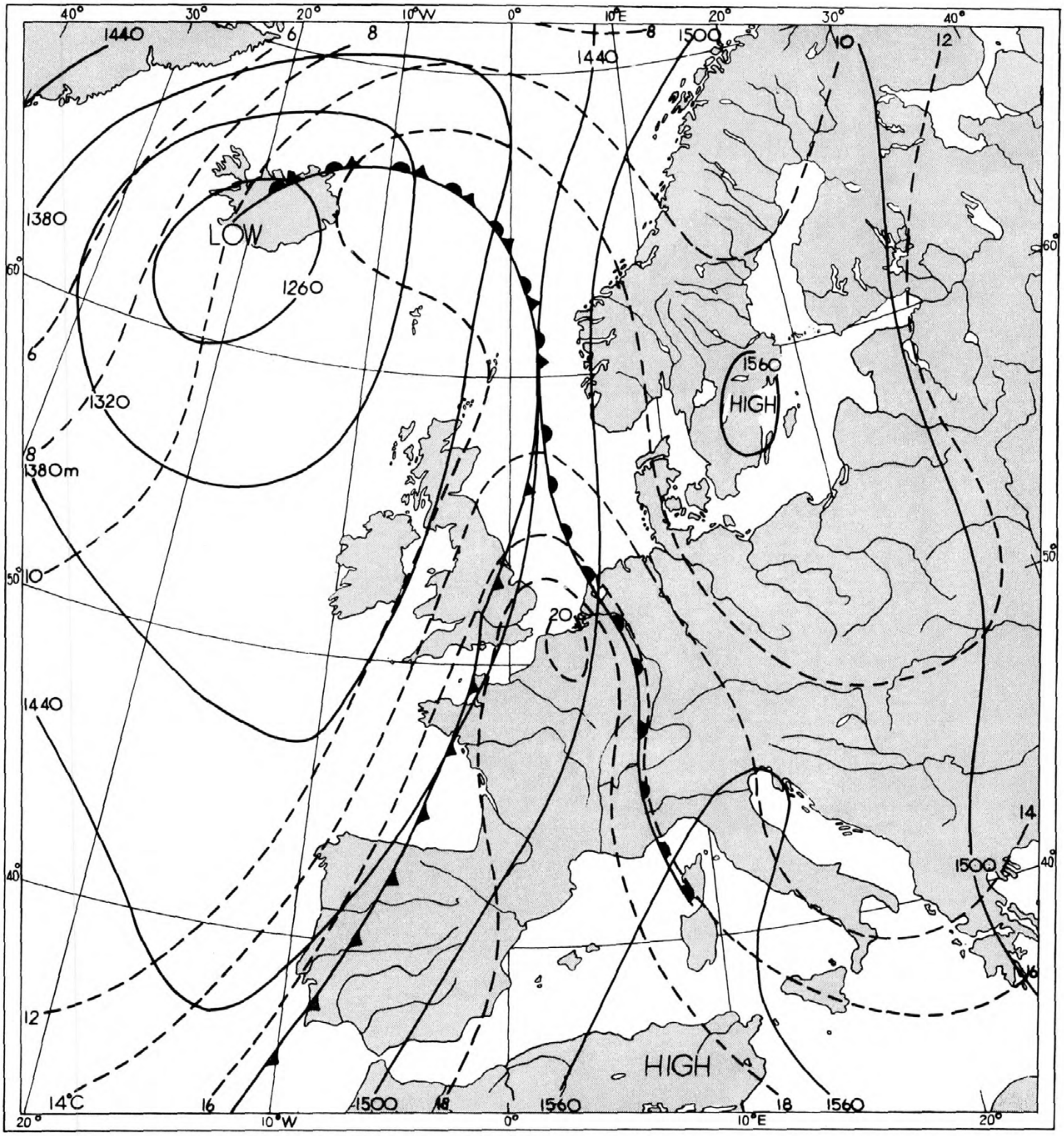

40°
30°
20°
10°W
0°
10°E
20°
30°
40°
1440
6
8
8
1500
1440
10
12
1380
LOW
60°
1260
6
1320
8
1380m
1560
HIGH
60°
50°
10
50°
20
1440
14
40°
1500
40°
16
12
14°C
16
1500
18
1560
HIGH
18
1560
20°
10°W
0°
10°E
20°

FIGURE 39(*a*)—CONTOURS, ISOPLETHS OF WET-BULB POTENTIAL TEMPERATURE AND FRONTS, AT 850 MB, 1200 GMT, 28 AUGUST 1958

Contours are shown by continuous lines and isopleths of wet-bulb potential temperature by dashed lines.

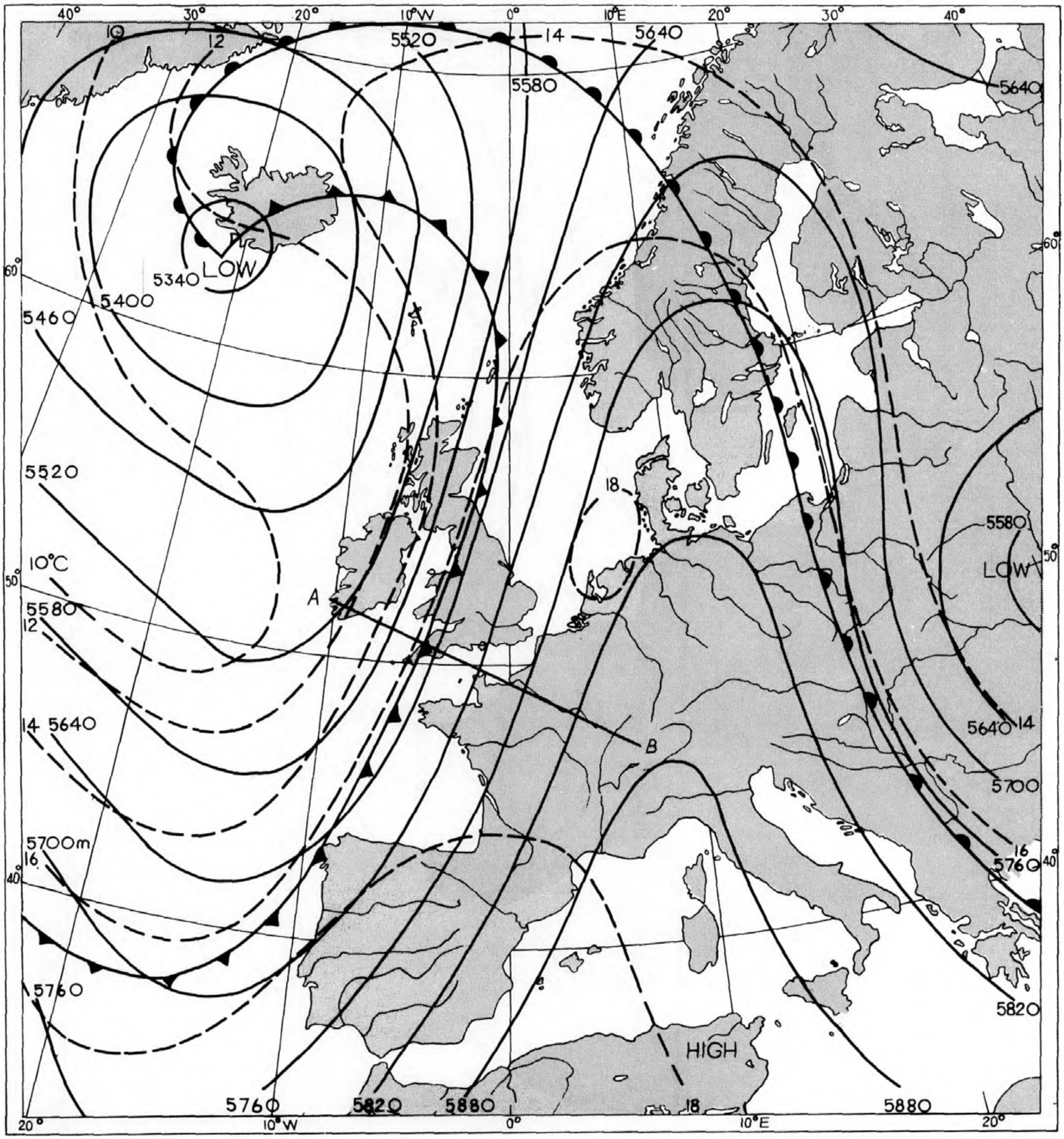

40°
30°
20°
10°W
0°
10°E
20°
30°
40°
10
12
5520
14
5640
5580
5640
LOW
5340
5400
5460
60°
5520
18
10°C
50°
5580
12
A
14 5640
B
5580
LOW
50°
5640 14
5700
5700m
16
40°
16
5760
5760
5820
HIGH
5760
5820
5880
18
5880
20°
10°W
0°
10°E
20°

FIGURE 39(*b*)—CONTOURS, ISOPLETHS OF WET-BULB POTENTIAL TEMPERATURE AND FRONTS, AT 500 MB, 1200 GMT, 28 AUGUST 1958

Contours are shown by continuous lines and isopleths of wet-bulb potential temperature by dashed lines. *AB* is the line of cross-section shown in Figure 41.

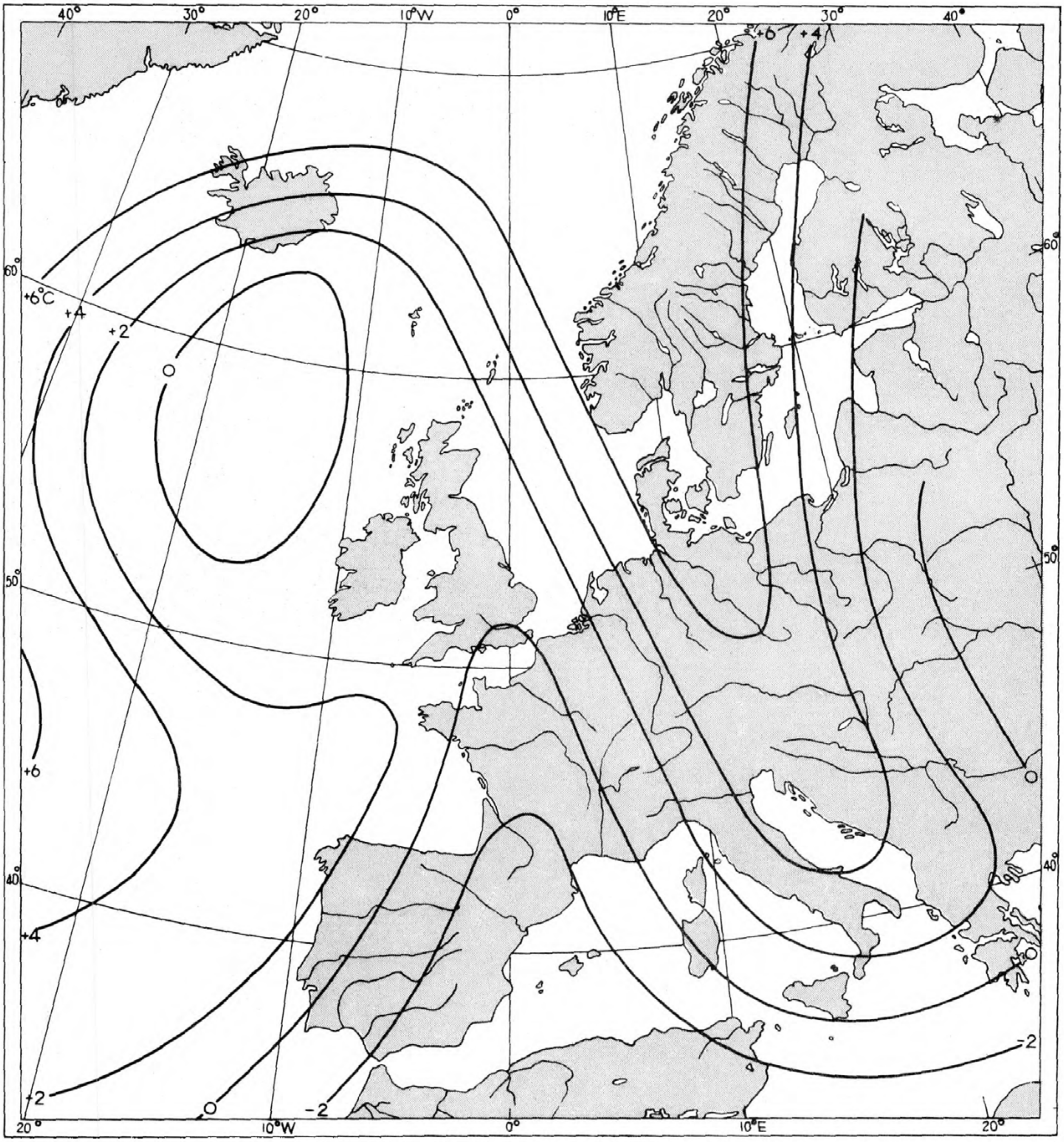

40°
30°
20°
10°W
0°
10°E
20°
30°
40°
+6
+4
60°
+6°C
+4
+2
0
50°
+6
40°
+4
+2
0
-2
60°
50°
40°
0
0
-2
20°
10°W
0°
10°E
20°

FIGURE 40(*a*)—DIFFERENCE OF WET-BULB POTENTIAL TEMPERATURE BETWEEN 850 AND 500 MB, SUBTRACTING THE FORMER FROM THE LATTER, 0001 GMT, 28 AUGUST 1958
Negative values indicate potential instability.

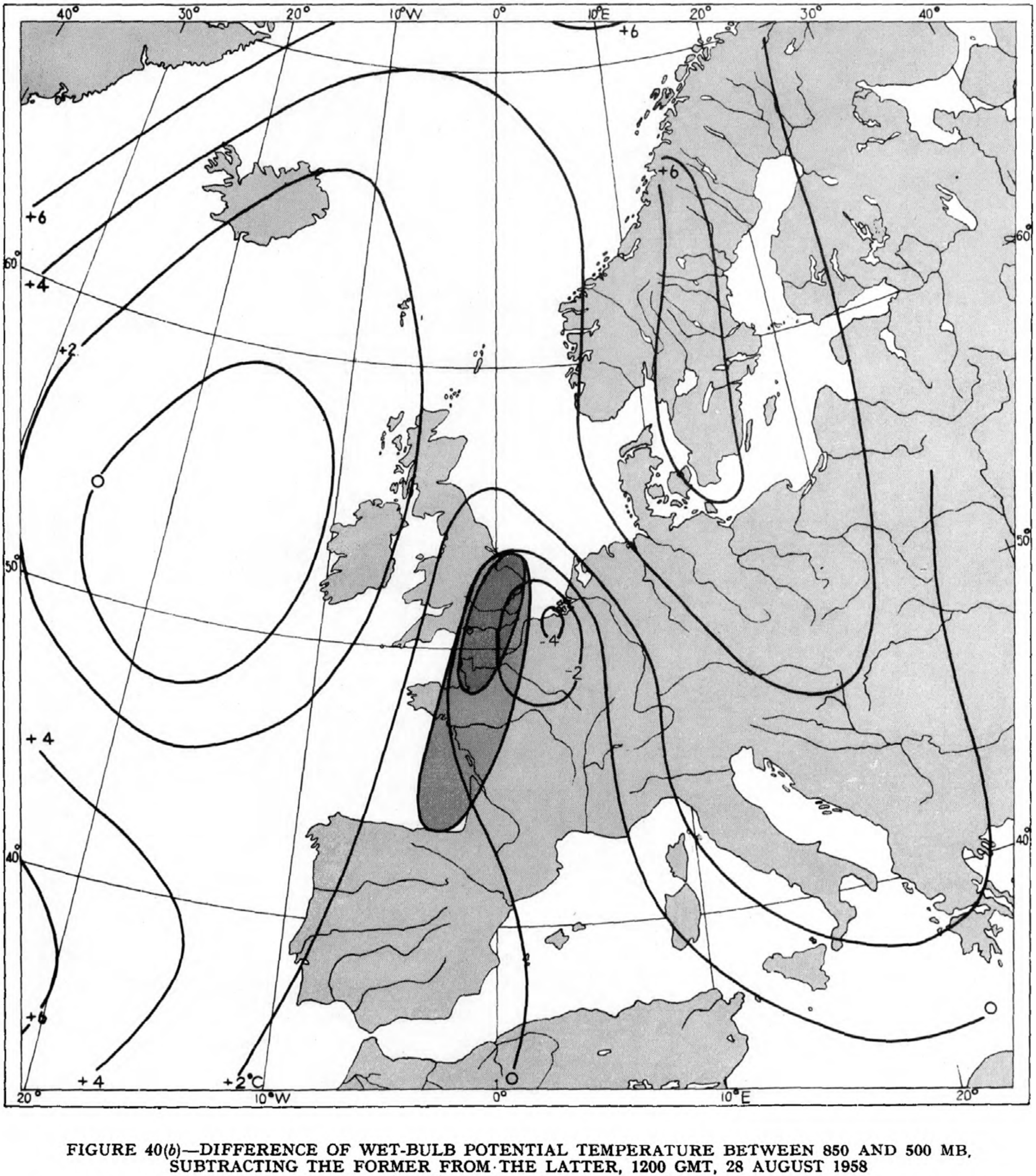

40°
30°
20°
10°W
0°
10°E
20°
30°
40°
+6
+6
+6
+4
60°
+2
O
50°
-4
-2
+4
40
50
60
O
2
+6
+4
+2°C
O
20°
10°W
0°
10°E
20°

FIGURE 40(*b*)—DIFFERENCE OF WET-BULB POTENTIAL TEMPERATURE BETWEEN 850 AND 500 MB, SUBTRACTING THE FORMER FROM THE LATTER, 1200 GMT, 28 AUGUST 1958

Negative values indicate potential instability.

Heavy shading shows the area of thunderstorms existing at 1200 GMT; medium shading shows the area over which thunderstorms occurred during the period 0600 to 1200 GMT.

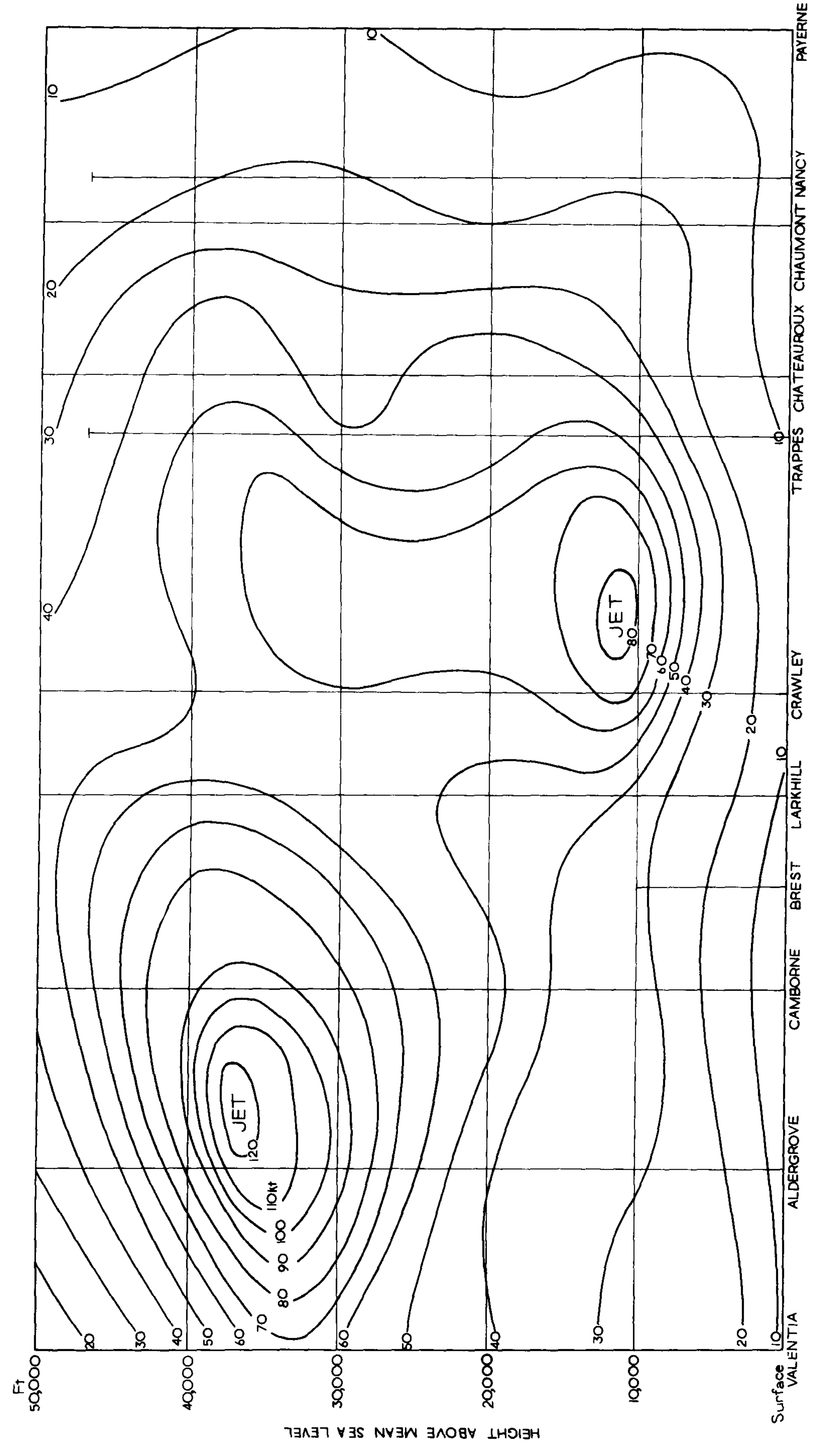


FIGURE 41—VERTICAL CROSS-SECTION FROM VALENTIA (IRELAND) TO PAYERNE (SWITZERLAND) FOR 1200 GMT, 28 AUGUST 1958

The isopleths are the wind component perpendicular to the line of section (line *AB* on Figure 39(*b*)), that is, blowing from 200°.

Penn[53], in a case study of thunderstorms over New England, found that low-level convergence combined its effect with divergence aloft. Beebe and Bates[54] have proposed that this combination can be brought about by appropriate jet structures at different levels. In particular, they give much empirical evidence to show that divergence is especially favoured at the left exit of a cyclonically curved jet, and at the right entrance of an anticyclonically curved jet.

With the storms under study, Figures 38 and 39 show that there was little change in the wind pattern at 500 millibars between midnight and midday. Throughout the period of the storms a trough was very slow-moving just to the west of Britain with its axis lying north to south. Consequently the trajectories of air parcels crossing Britain at 500 millibars may be considered as being parallel to the contours at that level. These contours show decreasing cyclonic curvature downwind—a pattern in which divergence will be present because a parcel moving through it will be accelerated in an attempt to maintain gradient wind speed. This divergence was persistent over a large area of north-west Europe, but it was probably weak; no large pressure tendencies were reported at the surface (except those caused by meso-systems). Convergence at low levels was difficult to detect; if present it was probably very weak but perhaps greatest near the feeble wave on the cold front.

We may summarize the conditions present which were necessary for the origination of the storms as:

(i) potential instability brought about by differential advection in such a way that warm, moist air was advected into the storm region most quickly at low levels;

(ii) divergence aloft associated with a jet stream downwind of the axis of a slow-moving trough. Low-level convergence may have been present, especially near the shallow wave on the cold front.

These conditions conform well to those shown on the composite charts prepared by Baird[55] to represent the synoptic features of squall-line situations.

When the macro-scale processes necessary for the formation of the storms have been operating for a sufficient length of time, the first storms make their appearance. Their places of origin no doubt depend upon small and localized variations in the properties of the air mass in which they form, particularly variations of humidity and of vertical motion such as may be found over hilly country. As a consequence it would be very difficult to predict the location and time of occurrence of the first storms. However, the macro-scale processes are likely to delimit a fairly definite region within which all of the original storms appear. Both the size of this and its movement across country would be controlled by changes in the macro-scale processes producing it. Almost invariably it would move at a speed less than that of the winds within it, particularly the winds at higher levels, say, above 10,000 feet. Hence these winds would blow through the area, entering at the rear and leaving at the forward edge, and they would carry the developing storms with them. Whilst these storms are lying within the development area they will continue to grow, but after moving outside its boundary they will cease development. If they move farther, into a region where the macro-scale processes are actively against growth, then the storms will decay rapidly. However, if the storms reach a stage when they become self-propagating they may continue to grow in a region otherwise unfavourable to the formation of new storms.

The size of the development area is likely to increase as the effects of the macro-scale processes become more pronounced. Because of this, the period of time spent by any individual storm within the area will also increase, thus allowing it to develop further, even to the extent of producing a meso-system. However, the size of the development area need not increase uniformly as it too will be controlled by local inhomogeneities within the air mass and by variations in vertical motion of perhaps an orographic or diurnal nature. These facts make it very difficult to predict the time period over which any existing storm or system is likely to continue developing.

In this study, the succession of meso-systems crossing south-east England eventually produced an elongated band of disturbed weather lying almost north–south and several hundred miles in length. It resembled the squall lines which are well-defined features of the weather over the middle and eastern United States of America. Although the complete succession could not be surveyed because it lay over the North Sea, it is reasonable to suppose that it consisted of the fused remains of the several meso-systems, each at a different stage of development or decay. Observations from Belgium, the Netherlands and extreme north-west Germany later in the afternoon indicated that new storms continued to develop at the southern end. Fujita[21] and Brown[56] are among those who have shown that squall lines are composed of a series of meso-systems, each of which forms and develops independently of the remainder. The final result is a system which is of macro-synoptic importance.

3.5 *Movement and propagation*

It was Levine[1] who was one of the first to point out that persistent storms lasting several hours or more must *propagate* through the atmosphere and not just move with it. In no other way can fresh air be constantly fed into the storm area. This implies that, on a given occasion, small isolated short-lived storms move in a different direction to large long-lived storms composed of numerous closely packed cells. Direct measurement of the difference has been difficult because the storms are usually both too large for visual observation, and at the same time too small for study by the ordinary synoptic network. Not until radar had been used to follow the tracks of storms could the difference be seen. Brooks[57] found that a group tended to move in a direction to the right of that of the individual cells of which it was composed. This indicated that new cells were forming in the direction of the shear vector drawn from the cell velocity to the group velocity. Other investigators also found this displacement of the group velocity to the right of the cell velocity. (They included Newton and Newton[12], Newton[58], Stout and Hiser[59], Brown[60], Newton and Katz[61], Fujita and Brown[62] and Fujiwara[63].)

Table I shows some values of cell velocities for the storms under study. Each velocity is a mean value for the time intervals shown. The direction of motion seems to remain constant—from 199°—but the speed appears to increase from 53 knots to about 70 knots between 0748 and 1300 GMT. These speeds are consistent with the winds over south-east England shown on Figure 41 between 10,000 and 35,000 feet. The only large storm whose track is reliably shown by radar is that producing high C_1. Figure 42 illustrates successive positions shown by radar from 1000 to 1330 GMT. The areal extent is least at the extremities of the indicated path because at both places the radar can detect only the most intense cores of precipitation. A line joining these two ends gives a good indication of the apparent track of the most active part of the storm, and it shows that the storm propagated from a direction of 208° with a speed

TABLE I—SOME MEASURED VALUES OF CELL VELOCITIES

Time interval	Cell velocity Direction	Cell velocity Speed	Time interval	Cell velocity Direction	Cell velocity Speed
GMT	° *true*	*knots*	*GMT*	° *true*	*knots*
0748–0815	198	53	1015–1030	196	70
0815–0830	199	53	Mean 0748–1030	199	57
0830–0845	201	52			
0845–0900	204	55	1145–1200	202	62
0900–0915	199	57	1200–1215	196	66
0915–0930	200	56	1215–1230	198	70
0930–0945	200	55	1230–1245	202	74
0945–1000	198	59	1245–1300	196	55
1000–1015	200	58	Mean 1145–1300	199	65

of 61 knots. This direction was confirmed exactly by tracking the storm mass using hourly positions obtained by location of atmospherics over an eight-hour period. Hence this large storm moved in a direction to the right of the motion of the single cells, that is, the storm mass propagated itself across the wind flow with a deviation of 9°.

The reason for propagation is that new cells are continuously developing in a preferred direction from the position of the existing cells with a velocity of propagation represented by P in Figure 43. The process may be considered as being the result of the appearance of a succession of new cells at a point—the generating point—which itself is moving in a direction to the right of the motion of the cells. Figure 44 shows successive positions of a band of cells at times $t = 0$, $t = 1$, etc., until $t = 5$. At $t = 0$, cell I is just forming. By the time $t = 1$, cell I has moved and cell II is just forming in a direction from it given by the vector P of Figure 43. Hence the generating point has moved from A to B. By the time $t = 2$, both cells I and II have moved farther and cell III is just forming, again in the direction given by vector P, so that the generating point has moved farther, up to C. As this process continues, the row of cells grows in length and its orientation is clearly controlled by the direction of vector P.

At $t = 4$, four cells are in existence with a fifth just forming at the new position of the generating point, E. If the time period from $t = 0$ to $t = 4$ is comparable with the life-cycle of an individual cell, then cell I will be in the last stage of decay. By the time $t = 5$, cell I will have disappeared, and although the orientation of the band will have remained the same the band will have been displaced to the right of the direction of motion of the individual cells. In fact, as the band continues to move, the oldest cells (at the left-hand end) decay as fast as new cells (at the right-hand end) form so that the storm mass as a whole moves with the velocity of the generating point.

The length of the band of cells is determined by the speed of propagation and the life of an individual cell. If these are P knots and T hours, respectively, then the band-length will be $P \times T$ nautical miles.

We have now seen that the velocity of propagation controls three properties of the band of cells:

(i) its velocity as a whole, since this is the vector sum of the cell velocity and the velocity of propagation;

(ii) its orientation, which is in the same direction as that of propagation;

(iii) its length.

The propagation velocity itself is controlled by the position and rate of appearance of new cells around the existing ones. Many studies, especially the Thunderstorm Project, have shown that new cells are often " triggered " by the local convergence which exists where the downdraught of an older cell interacts with its surroundings. The magnitude of the convergence depends upon the difference in velocities of the downdraught and of its surroundings. If the initial storm is stationary or if no vertical shear is present, then the speed with which the downdraught spreads out radially from the cell's centre, compared with the speed of the surroundings, will be the same in all directions. Hence there will be no preferred direction in which new cells appear. Instead, the system expands with the new cells lying approximately along a circle with its centre at the position of the initial cell (relative to its surroundings, not to the ground). Fujita[14] has found this in a study of some slow-moving systems. If the initial storm develops in an atmosphere possessing vertical shear, then the downdraught at low levels is likely to possess a velocity relative to that of its surroundings which varies with direction from the centre. Thus, in Figure 45, if D and L represent the velocities of the spreading downdraught and of the environment wind at low levels, respectively, then the vector, P, will give the direction of propagation (Newton and Katz[61]). Where the wind veers with height, such as occurs when warm advection is taking place, this vector is to the right of D and hence to the right of the cell velocity since

D is unlikely to be much different from the velocity of the cell within which the downdraught develops (unless considerable shear exists *inside* the cloud). Newton[58] has shown that propagation to the right will occur even if the wind direction does not change with height as long as the speed increases with height.

It is clear then that propagation is the result of development of deep convection within a layer possessing vertical shear. However, observation of *isolated* cumulonimbus clouds shows that vertical shear tends to destroy them, with their tops streaming downwind at high levels. This is because mixing of the cloudy air with its surroundings is so effective with a relatively narrow cloud that vertical shear within it is almost as large as in its surroundings, so that there is little difference between the velocities of the cloud and its surroundings. But when the storm becomes massive, perhaps ten or twenty miles across, mixing is less effective and in-cloud shear is small. Also, since much of the in-cloud air is derived from lower levels, its mean speed measured throughout the depth of the cloud will be less than the mean speed through the same depth of surroundings. Hence there is a greater contrast between the velocities of a massive cloud and its surroundings. If the storm is massive enough, this contrast will become sufficient to make propagation possible in a preferred direction.

A massive storm will continue to propagate itself across the winds as long as it is in a region of strong vertical shear. Newton and Katz[61] have suggested that the velocity of propagation is determined by the magnitude of the shear. If the storm propagates into a region of little or no shear (as would be found to the right of the warm ridge or in the region of warm advection where it started) then it will die out. Both Macdonald[32] and Newton[58] have pointed this out. If the storm propagates into a region of shear having no change of direction with height, then the velocity of propagation, as shown by P in Figure 43, will be parallel to the cell velocity and so, too, will be the orientation of the band, which will therefore move only in a direction parallel to itself. This progressive change in the orientation of the band, with an accompanying slowing down of its motion perpendicular to itself, seems to be a feature of some squall lines. The band of cells accompanying highs C_1 and C_2 showed progressive re-orientation as it crossed England into the North Sea.

It is possible for the generating point to be almost stationary. This occurs when the propagating velocity is approximately the reciprocal of the cell velocity, as can occur when vertical shear is present and the upper-level winds are light and variable. A succession of new cells then forms over approximately the same place, with the result that heavy rain becomes prolonged, leading to excessively large falls even exceeding ten inches in one day. Some storms of this type have been described by Stout and Hiser[59], by Fujiwara[63], by Huff, Semonin, Changnon and Jones[64], and by Fujiwara and Toya[65].

Hitschfeld[66], by studying radar echoes from different levels inside a large storm, has shown that there is little variation of echo velocity with height even when considerable vertical wind shear is present. The intense cores of large storms were found to remain approximately vertical, and they moved with a velocity influenced by the wind at low levels—probably the level at which convection originates, which may thus be regarded as a " steering level ". Where there is asymmetry in the flow at this level a storm grows in a preferred direction, thus leading to a storm velocity which can differ greatly from the wind velocity at any level. Such asymmetry of the flow is likely, for example, where the downdraughts of two adjacent storms interfere or where an isolated storm crosses an irregular land surface.

Although the core of a large storm remains nearly vertical in the presence of shear, those parts of the cloud which lose their buoyancy usually stream downshear in the form of a vast plume or anvil, detectable by radar and therefore containing particles of precipitation size as well as cloud particles. These precipitation particles are not the largest possible (large raindrops and hailstones) because such particles quickly fall out near the storm's core. Calculations by

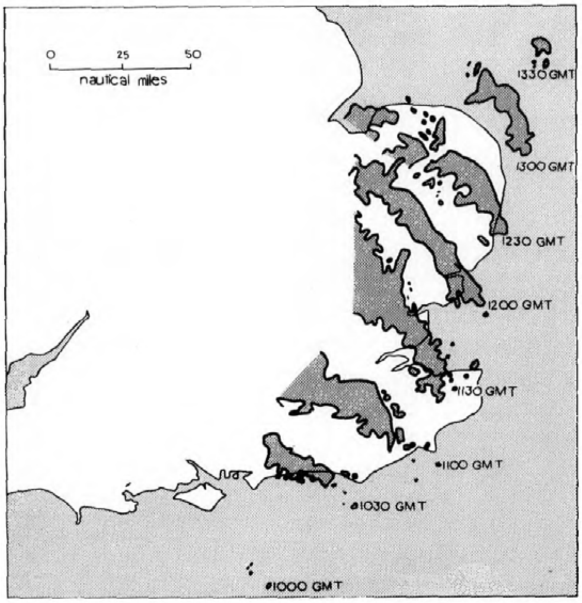

0 25 50
nautical miles
1330 GMT
1300 GMT
1230 GMT
1200 GMT
1130 GMT
1100 GMT
1030 GMT
1000 GMT

FIGURE 42—POSITIONS OF RADAR ECHOES FROM THE COMPOSITE STORM ASSOCIATED WITH HIGH C_1

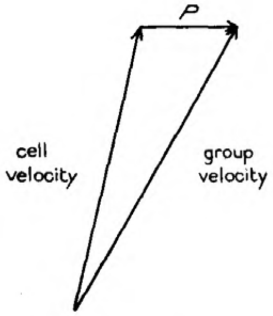

P
cell velocity
group velocity

FIGURE 43—VECTOR DIAGRAM SHOWING CELL, GROUP AND PROPAGATION (*P*) VELOCITIES

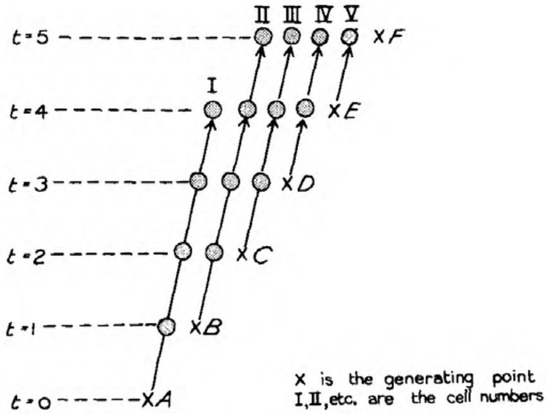

t=5
t=4
t=3
t=2
t=1
t=0
I
II III IV V
XA
XB
XC
XD
XE
XF
X is the generating point
I, II, etc. are the cell numbers

FIGURE 44—MOVEMENT OF A GROUP OF CELLS
This shows that the velocity of the group is composed of both the cell velocity and the velocity of the generating point (propagation velocity) as shown in Figure 43.

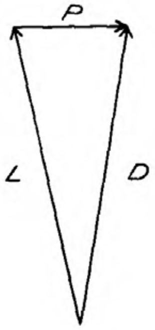


FIGURE 45—VECTOR DIAGRAM SHOWING VELOCITIES OF ENVIRONMENT AT LOW LEVELS (*L*), DOWNDRAUGHT (*D*) AND PROPAGATION (*P*)

Hitschfeld[66], based on the shapes of plumes, suggest that they are composed mostly of snowflakes and small hail. This is supported by two other pieces of evidence: firstly, the much smaller intensity of precipitation from such anvils (two to four millimetres per hour in this study); and secondly, a distinct " bright band " on the range height indicator radar display occurring near the 0° C level where the ice particles melt to raindrops. In this study, a " bright band " at 9,000 to 10,000 feet was a well-marked feature of the rain areas away from the intense storms. Imai[67] has made similar observations of a " bright band " in a study of a decaying storm.

The horizontal extent of an anvil caused by wind shear will depend upon:

(i) the difference in velocities of the core and of the surrounding wind at the level of the anvil's top,

(ii) the anvil's age,

(iii) the effectiveness of evaporation and sublimation into the anvil's surroundings (especially the air below the anvil into which the precipitation falls).

Where the shear is in a direction opposite to that of the storm's motion (as occurred to a small extent in the upper half of the troposphere for the case under study—see Figure 41) an anvil top lags behind the storm's core and to an extent which increases with its age. Thus, after several hours, the rain areas associated with systems *B* and *C* had grown to become 50 miles broad.

§ 4—A " MODEL MESO-SYSTEM "

4.1 *Introduction*

It seems reasonable to suppose that all of the meso-systems *A* to *F* described in Section 3.2 were developing in a similar way, but that each system crossed England at a different stage. By combining the properties of the observed systems it is possible to obtain a detailed description of the structure and life-cycle of a " model " system. It was, indeed, fortunate that these systems had different life-spans and that they crossed England during different stages in their development. This fortuitous combination of circumstances was particularly suitable to the deduction of the properties of a " model " system.

The initial stages in the development of the storms did not take place over England and therefore could not be studied by using the meso-synoptic data. The origin of the storms was controlled by processes on a macro-synoptic scale discussed earlier in Section 3.4. After initiation the storms continued to develop, and in so doing produced the meso-systems described in Section 3.2 Although some of the systems ceased development prematurely, the full life-cycle of a " model " system can be deduced quite easily. It may be divided into three stages whose main properties are as follows:

(i) Growth stage. Storms are isolated or in small groups. Local pressure rises develop, eventually merging into a thunderstorm high which then grows in areal extent and in amplitude along with a growing rain area.

(ii) Mature stage. The rainfall pattern becomes more organized with the separate storms being replaced progressively by a row of intense cells along the leading edge of the high together with a broad area of continuous rain behind it. This high is more intense and continues to grow in extent. Its leading edge is marked by a very large pressure gradient and its centre corresponds to the position of the most violent storms, which seem to be self-propagating and able to move in a direction across that of the winds at low levels. After some hours at this stage a " wake low " appears behind the high with pressures falling well below undisturbed values. The rear edge of the rain and thunder corresponds very well to the axis of this low.

(iii) Decay stage. The line of storms disappears, leaving a broad area of uniform rain which itself slowly disperses over a period of many hours. Although the areal extent of the system continues to increase, the magnitudes of the pressure fluctuations decrease until they become too small to be measured.

In the remainder of this section the detailed structure of each of these three stages will be considered. Figures 46 to 51 show the main features of each of the stages.

4.2 *Growth stage*

The first storms to appear are small and isolated. Their effect on the weather is typical of simple storms, being largely controlled by the downdraughts from individual cells. Pressure rises, wind changes and rain areas are localized and therefore unlikely to be detected by the widely spaced stations in the synoptic network. Probably the only way of tracking them satisfactorily is by using radar. Later, after an hour or two, as the number and concentration of storms increase and more particularly as large groups of storms appear, so the downdraughts from individual cells begin to merge. The mass of cold air produced in this way accumulates at low levels and then begins to affect the weather over a wide region, perhaps 100 miles across. Pressure rises of a few millibars are recorded from many stations within the region, and the meso-synoptic chart shows a distinct meso-high which is merely superimposed on the undisturbed isobars. At first its amplitude will vary from place to place, being controlled by the positioning of the most active centres. Its speed, too, is likely to be erratic, since its centre will tend to change as the position of the dominant storm changes. There may even be more than one centre. During this period the leading edge of the high becomes organized into a surge line with a rapid pressure rise behind it. As the system moves away, pressure returns to its undisturbed value.

Between the surge line and the axis of the high the pressure gradient can be exceedingly large, approaching extremes of one millibar per kilometre, with correspondingly enormous geostrophic winds. Fortunately such winds are never attained because any given parcel of air is subjected to the intense gradient for too short a period (see later in this section). The properties of surge lines were discovered when meso-synoptic charts were first prepared. Tepper[9] and Williams[68] were among the first who made very detailed studies of squall lines, using charts at one-minute and five-minute intervals respectively. Many of their results were observed in this case study. The larger scale of their analyses showed that the surge line is not straight but has irregularities which may be linked to the leading edges of individual storms. Ohsawa[69] has also pointed out that the surge line is the envelope of leading edges of small-scale highs associated with each storm. In this study the coarse spacing of stations over much of the analysis area made it impossible to find such fine detail.

Winds at first are disturbed only by the isolated downdraughts, but even a quick glance at the meso-synoptic maps of Section 3.1 shows that nothing like a geostrophic balance is achieved inside the meso-systems. Between the surge line and the axis of the thunderstorm high, where the pressure gradient is very large, the only important horizontal force acting upon a parcel of air near the ground is that caused by the pressure gradient. Forces resulting from friction and the geostrophic effect are much smaller and may therefore be ignored. Consequently, the wind blows perpendicularly to the isobars in a direction from high to low pressure and with constant acceleration. Each meso-high moves at a speed considerably greater than the winds at low levels in the environment, so that a given parcel of air is subjected alternately to strong gradients, first ahead of and later behind the axis of each high. It is far from correct to assume that the air near the ground travels along with each high. Because of the speed of each high, a parcel of air is subjected to the intense pressure gradient behind the surge line for only a short time (five to ten minutes in the mature stage) so that the final wind speed is still small. Commonly observed speeds are 10 to 15 knots with gusts to 25 knots.

Much stronger winds than those observed might have been expected as a result of horizontal spreading near the ground of the powerful downdraughts in the storms. Although the downdraughts undoubtedly did spread below the storms, they were prevented from reaching the ground by a cold film of air there which had persisted from the radiational cooling of the previous night. Because of this some observers were able to report that fragments of low cloud (presumably in the spreading downdraughts) were moving rapidly whilst little wind occurred at the ground. This protective cold film no doubt made the storms under study somewhat unusual. If a large lapse rate had extended from the ground upwards the downdraughts would have been able to reach the ground. With the storms under study the air behind the surge line is the same as that ahead of it, but in a situation where the downdraughts reached the ground the air behind the surge line would have been different from that ahead of it.

The squall winds in the spreading downdraught would not everywhere be governed by a single dominant force—the pressure gradient force. This can perhaps be seen by considering the magnitudes of the pressure gradients caused by a single downdraught. The magnitude is determined by the slope of the upper surface of the spreading cold air, which in turn varies with both distance from the storm centre and with time at a given distance from the centre. Near the centre the gradient will be large so that the pressure gradient force will be very much greater than both the Coriolis and frictional forces. Farther away, and especially near the edges of a cold downdraught, the pressure gradient force decreases to become comparable with friction (which has increased with approximately the square of the wind speed) but is still greater than the Coriolis force (which has increased linearly with the wind speed). Thus, near the storm's core the spreading downdraught is subjected to linear acceleration, but near the expanding edges flow is approximately balanced under the influence of the pressure gradient force and friction.

Following a parcel of air which moves just behind the edge of the spreading downdraught, at first it undergoes linear acceleration from a position beneath the core (where it has zero horizontal velocity) to a point say ten miles from the core after 20 minutes when its speed is perhaps 60 knots. By this time the pressure gradient force will have decreased but friction will have increased, giving an approximately balanced flow. Proof of such changes of gradient cannot be determined from the relatively coarse spacing of observing stations in this report; a widespread micro-synoptic network would be required.

As the boundaries of the downdraught continue to expand, squall speeds will decrease. This is because, with a given rate of production of cold air within the core, the radial rate of transfer of mass is approximately constant. But since this transfer is distributed over a continuously growing circumference the radial speed must decrease outwards. Although the rate of mass transfer will largely depend in the first place on the rate of production of cold air, later, when this production has ceased, the rate will be controlled by subsidence of the existing mass of cold air. Continuous adjustment of the slope of the upper surface of this cold air will take place in response to these changes of wind speed.

With a self-propagating storm mass, air behind the surge line is continuously being replaced (or at least diluted) by fresh cold air from above, and it does not remain for long periods in the region of linear acceleration. Farther away from the active centres, approximately balanced flow is reached.

Behind the axis of the high the pressure gradient is usually weaker and orientated in a different direction so that a parcel of air, having been accelerated in the direction of motion of the system by the gradient behind the surge line, is soon accelerated in a new direction, thus causing a progressive veering or backing of the surface wind. If the centre of the high passes to the right of a station (standing with one's back to the direction of motion of its centre) the wind backs, but if it passes to the left the wind veers. A roughly radial wind field is thus set up, but its centre does not correspond to the centre of the high because the speed of the high is so great that by the time the gradients in its rear have produced a noticeable backing or veering of the wind (after some five or ten minutes) it has moved on five or ten miles. Consequently, the line separating forward-moving air (that is, with a component in the direction of motion of the high) from backward-moving air lies some ten miles to the rear of the axis of the high. In particular, for a station where the centre of the high passes overhead, the wind reverses (as a result of the reversal of gradients) but the change occurs later than the time of maximum pressure, so that between these two instants the wind is actually blowing towards high pressure. At such a place the wind speed would increase uniformly to reach a maximum at the time of maximum pressure, and then it would decrease uniformly whilst the pressure was falling until it reversed and then increased again. This lag between changes of wind direction and of pressure gradient has been noted also by Tepper[9], by Williams[68] and by Blackmer, Holleyman and Gibson[70].

The first rainfall is heavy, consisting of large drops, but localized and short-lived, each cell lasting perhaps half an hour or one hour as it moves across country. Progressively the concentration of cells increases with a distinct tendency to appear in groups, some of which develop into violent storms with intense rainfall and perhaps hail. Groups of cells can be tracked for periods of more than one hour. The spreading tops of the clouds gradually combine and from them fall periods of more continuous but less heavy rain. New cells develop throughout the region covered by the meso-high without any obviously preferred areas. As a consequence the most violent storms may be found anywhere from just behind the surge line to well behind the axis of the high.

Clouds are mostly altocumulus species typical of instability at medium levels—floccus and castellanus—and they are present in large amounts. In the initial storms the cloud becomes massive and may be considered as cumulonimbus at medium levels. After about an hour the spreading tops give patchy cloud at higher levels, and gradually these patches merge into extensive areas of nimbostratus and altostratus cumulonimbogenitus from which the lighter rain falls.

Individual cells produce thunder and lightning for only short periods (perhaps ten or twenty minutes) but the more persistent groups of cells give violent storms which can be followed for perhaps an hour or more.

Figure 46 shows a typical meso-synoptic map representing this stage, and Figure 47 shows a vertical cross-section along the line *AB* of Figure 46.

4.3 *Mature stage*

The growth stage is typified by the weather systems becoming progressively more organized. After a few hours an approximately " steady state " is reached which then can persist for several hours more without much general change. This is the mature stage.

Pressure rises have reached a maximum amplitude, but the areal extent of the meso-high continues to increase as the combined cold downdraughts continue to spread outwards from the active centres. The surge line marking the leading edge of the high is very well marked and is followed by a sudden jump in pressure, which in extreme cases has been felt on the ears directly. The centre of the high lies just behind this surge line near its mid-point, but it tends to migrate to the right as it gets older, corresponding to the movement of the band of most active cells. During the mature stage pressure falls in the rear of the high until eventually a " wake low " appears whose central pressure is a few millibars below the undisturbed value. This low moves with a speed similar to that of the high ahead of it, but its track is more to the left. Pressure tendencies as the low passes a station are almost as large as those observed near the high. Where isobars cross the boundaries of a system they are usually kinked, corresponding to abrupt changes on the barograms. But in the oldest and weakest parts of a system, changes are more gradual and the isobars may not be as sharply kinked as shown on the charts.

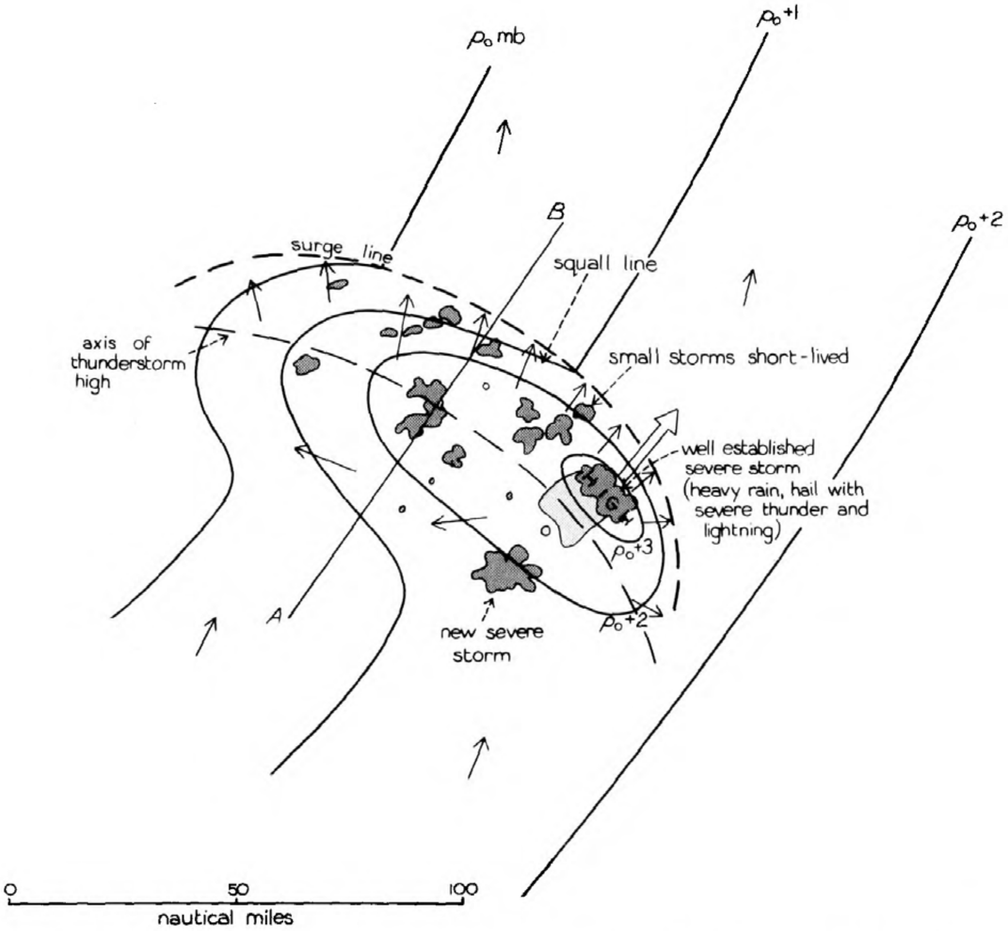

p₀ mb
p₀+1
p₀+2
B
surge line
squall line
axis of thunderstorm high
small storms short-lived
well established severe storm (heavy rain, hail with severe thunder and lightning)
HIGH
p₀+3
p₀+2
A
new severe storm
0
50
100
nautical miles

FIGURE 46—GROWTH STAGE OF A MODEL MESO-SCALE THUNDERSTORM SYSTEM
Light and heavy shading represent areas of light and heavy precipitation, respectively. Arrows show surface wind direction.

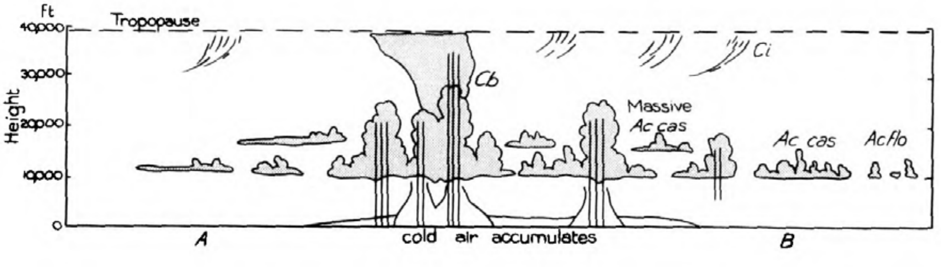

Ft
40000
30000
20000
10000
0
Height
Tropopause
Ci
Cb
Massive Ac cas
Ac cas
Ac flo
A
cold air accumulates
B

FIGURE 47—VERTICAL CROSS-SECTION ALONG THE LINE *AB* IN FIGURE 46

Behind the surge line a squall blows outwards from the high's axis across the isobars. The more complex shape of the system when both high and low are present means that pressure gradients are constantly changing as the system moves overhead so that the winds behind the axis of the high do not always have sufficient time to adjust their directions perpendicular to the isobars. In general, however, the flow continues outwards from the high, but just behind the axis of the high, winds may be seen blowing in the opposite direction for a short while, and the same may be seen just behind the axis of the low.

By the time that the mature stage has been reached the rainfall pattern has become simpler. Along the leading edge is a row of intense cells some 50 miles long which persists for several hours as it crosses the country. All new cells in the system develop here, especially at its right-hand end, so that the row as a whole tends to propagate to the right with the centre of the meso-high accompanying it. Once this row of intense cells has appeared it seems to be self-propagating without much change in its general appearance. It produces a formidable band of violent storms with rainfall rates well above one inch per hour and with local hail. Behind these storms there extends a broad area of continuous rain with remarkably uniform intensities. It falls from extensive nimbostratus produced by the storms. The rear edge closely coincides with the axis of the wake low.

Very similar relationships between pressure changes and precipitation have been found by other investigators, for example, Brooks[18], Fujita[21], Fujita and Brown[62], Blackmer, Holleyman and Gibson[70], Williams [71, 72] and Asnani[73].

Much of the cloud in the meso-system is of the layered type—nimbostratus and altostratus—slowly decaying but with some altocumulus floccus and castellanus beneath, but the leading edge where the violent storms occur contains massive actively growing cumulonimbus, still at medium levels. Behind the wake low much of the medium cloud disperses, thus allowing normal heating of the ground to produce cumulus clouds. In the rain areas, air moistened by evaporation of rain and lifted by turbulence produces stratus clouds.

Thunderstorms are violent but short-lived in the leading part of the system, and damaging lightning occurs over a wide area swept out by the band of storms. Occasional thunder is also observed in the more continuous rain shield.

Figure 48 shows a typical meso-synoptic map representing this stage, and Figure 49 shows a vertical cross-section along the line *AB* of Figure 48.

4.4 *Decay stage*

When the band of intense storms along the leading edge of the meso-high in the mature stage advances so far from the general region of development of new cells that the macro-scale processes are able to nullify its self-propagating nature, then new convection ceases and the band rapidly decays, leaving only the wide region of fairly uniform rain.

The production of cold air slows down and the existing cold air continues to spread outwards so that the areal extent of the system still increases but its amplitude decreases. Centres in the isobars become weaker until only ridges and troughs are present. Also the gradients decrease, so that the effect of the system on the winds becomes smaller. Rain continues to fall from the existing stratiform clouds but, as these are not being replenished by active convective centres, after a few hours they are exhausted, the rainfall becoming lighter still and more sporadic until it ceases altogether. There is no hail and little or no thunder.

Clouds are mostly altostratus and nimbostratus, but near the edges of the system altocumulus stratiformis and lenticularis are present although locally there may still be altocumulus floccus and castellanus.

Figure 50 shows a typical meso-synoptic map representing this stage, and Figure 51 shows a vertical cross-section along the line *AB* of Figure 50.

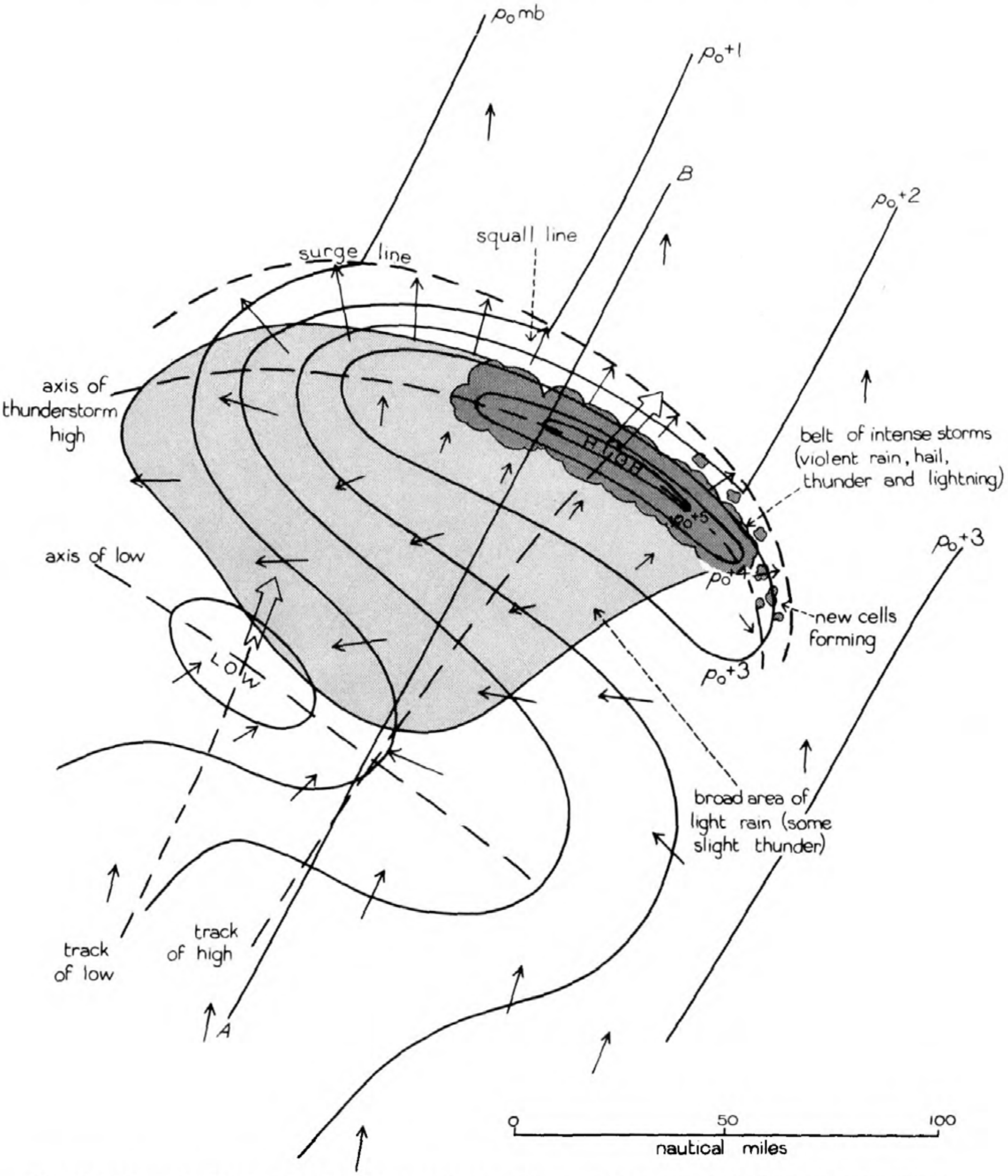

p_0 mb
p_0+1
B
p_0+2
squall line
surge line
axis of thunderstorm high
HIGH
belt of intense storms (violent rain, hail, thunder and lightning)
p_0+5
p_0+4
p_0+3
p_0+3
new cells forming
axis of low
LOW
broad area of light rain (some slight thunder)
track of low
track of high
A
0
50
100
nautical miles

FIGURE 48—MATURE STAGE OF A MODEL MESO-SCALE THUNDERSTORM SYSTEM
Light and heavy shading represent areas of light and heavy precipitation, respectively. Arrows show surface wind direction.

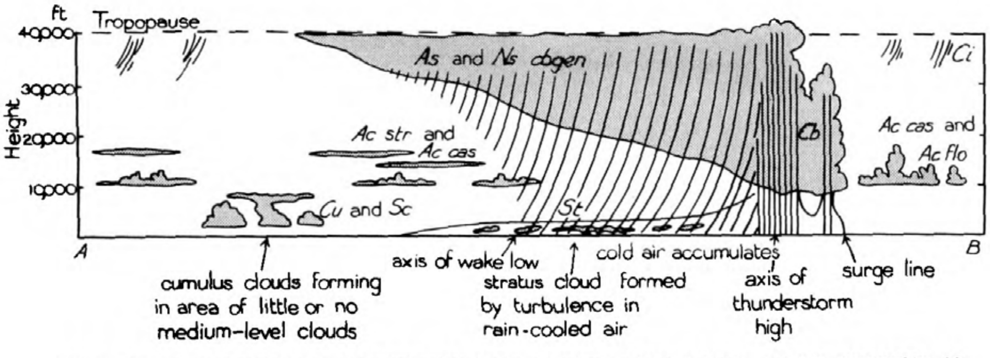

ft
Tropopause
40000
30000
20000
10000
Height
As and Ns cbgen
Ci
Ac str and
Ac cas
Cb
Ac cas and
Ac flo
Cu and Sc
St
A
B
cumulus clouds forming in area of little or no medium-level clouds
axis of wake low
stratus cloud formed by turbulence in rain-cooled air
cold air accumulates
axis of thunderstorm high
surge line

FIGURE 49—VERTICAL CROSS-SECTION ALONG THE LINE *AB* IN FIGURE 48

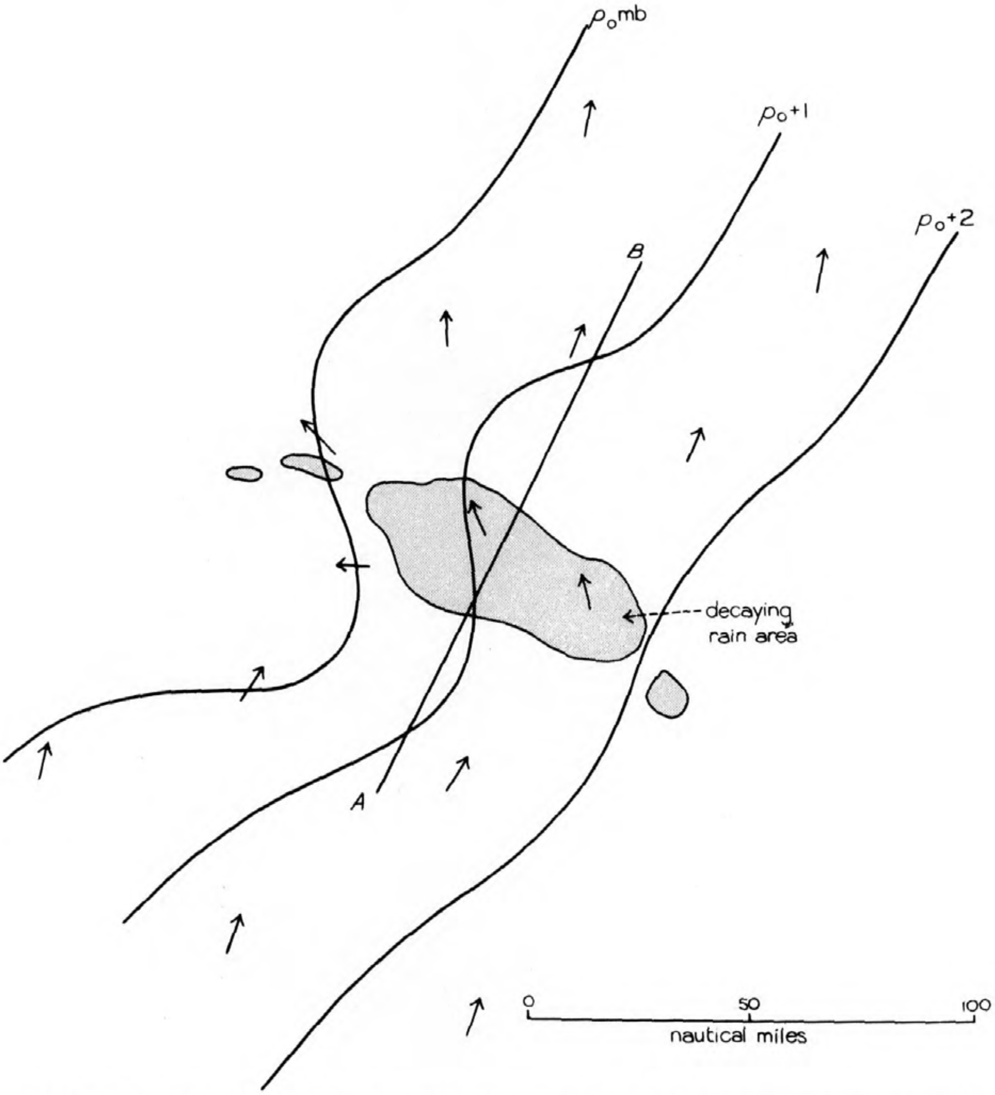

$p_0$mb
p_0+1
p_0+2
B
A
decaying rain area
0
50
100
nautical miles

FIGURE 50—DECAY STAGE OF A MODEL MESO-SCALE THUNDERSTORM SYSTEM
Shading represents areas of light precipitation. Arrows show surface wind direction.

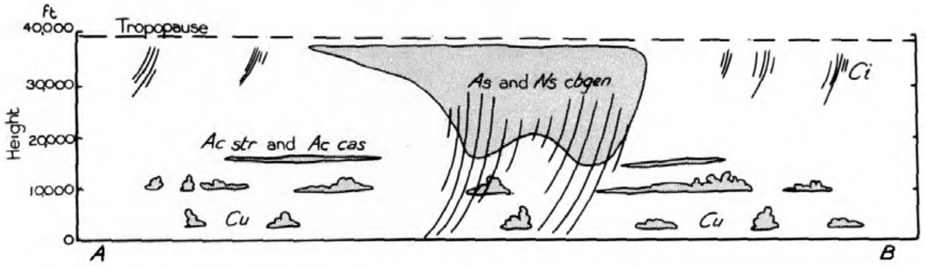

ft
40,000
30,000
20,000
10,000
0
Height
Tropopause
As and Ns cbgen
Ci
Ac str and Ac cas
Cu
Cu
A
B

FIGURE 51—VERTICAL CROSS-SECTION ALONG THE LINE *AB* IN FIGURE 50

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Corrections

PAGE 22, line 29: *For* "31" *read* "33"

PAGE 22, line 30: *For* "7" *read* "10"

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